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Syntax, the brain, and linguistic theory: A critical reassessment

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Syntax, the brain, and linguistic theory: A critical reassessment

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Editorial: Syntax, the brain, and linguistic theory: a critical reassessment

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Editorial on the Research Topic
Syntax, the brain, and linguistic theory: a critical reassessment

Introduction

Theoretical syntax no longer plays as prominent a role in neurolinguistics as it used to. A prominent issue is that linguistic theory often has been applied directly to neuroscience (Figure 1, left), but rather should be filtered through a well-articulated processing model (Figure 1, right). The papers in this volume pave the way for a renewed and productive relationship between linguistic theory and neuroscience in the study of syntax and the brain.

"Words" are not separable from syntax

A major insight that has guided recent research on the organization of syntax in the brain concerns the tight relationship between syntactic structure and the lexicon. Krauska and Lau review cross-linguistic evidence both from non-European languages such as Iniktitut, Vietnamese, and Hiaki, as well as English and Dutch, illustrating that the concept of the lemma familiar from psycholinguistic research (e.g. Levelt, 1989) is untenable. They propose an alternative model of syntax and the brain in which the posterior temporal lobe generates both what we colloquially call "words" and "sentences". Gonering and Corina provide a comprehensive review of constructionist and generative syntactic theories and neuroscience research on syntactic processing, and advocate for a theory in which syntactic processing is widely distributed in a dual-stream architecture: a ventral stream for processing nouns and attributive modifiers, and a dorsal stream for processing verbs and relational modifiers (cf. Bornkessel-Schlesewsky and Schlesewsky, 2013). Finally, Matchin points out that lexical items have both syntactic and semantic properties, a consensus across many linguistic theories. Therefore, spatial overlap between lexicality (e.g. word > nonword) and syntactic effects (e.g. complex > simple structures) in functional neuroimaging studies does not provide evidence supporting an inseparability of syntax and semantics in the brain.

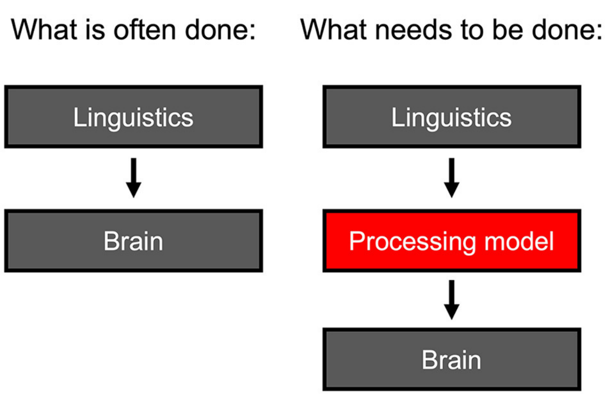

FIGURE 1
Left: some neurolinguistic work has attempted to directly apply linguistic theory to neuroscience, which has led to many pitfalls. **Right:** the approach we advocate here, in which linguistic theory is integrated with an adequate processing model, which will enable more meaningful results and the development of more effective neurocognitive models.

Syntactic deficits in patient populations are best explained by a combination of linguistic and domain-general deficits

Linguistic structure is clearly relevant to language disorders: agrammatism and cognitive impairments due to Alzheimer's disease can both be meaningfully characterized in part as a reduction in syntactic complexity. However, it is also critical to incorporate insights from cognitive domains outside of linguistics. Based on the results of Ivanova et al., deficits in working memory may explain some of the major declines in syntactic complexity yet preserved syntactic well-formedness in Alzheimer's disease. Faroqi-Shah claims that a combination of deficits to linguistic structure, speech articulation, and processing capacity may all contribute to the classic pattern of agrammatic speech commonly seen in nonfluent aphasia. Interestingly, Faroqi-Shah's framework takes a plausible middle-of-the-ground approach to agrammatism, differing from theories which focus primarily on deficits from a specific module of syntax derived from linguistic theory (e.g., Grodzinsky, 2000) and differing from theories which eschew any targeted linguistic deficit, but rather a more general processing issue (Kolk, 1995; Fedorenko et al., 2023).

Abstract linguistic structure is critical to online processing

It is common to dismiss the abstract structures that are postulated by some linguistic theories. However, the papers contributed by Greco et al. and Yamaguchi and Ohta indicate that these structures are essential for explaining language processing behavior. Specifically, Greco et al. illustrate the necessity of hierarchical structure to surprisal effects, above and beyond surface-based statistics based on specific words and parts-of-speech. Yamaguchi and Ohta investigated one issue that has often been contentious within the psycholinguistic literature: the extent to which putative phonologically null elements, or empty categories, exert effects on sentence processing similar to overt pronominal elements. They found evidence that the structures containing these putative null elements behave like structures with real reflexive pronouns, and also that multiple distinct types of empty categories must exist, converging with the predictions of syntactic theory.

Defining the relation between linguistics and neuroscience

One of the pitfalls in previous and current research on the syntax-brain relationship is the failure of sufficient imagination in considering how language might be implemented in the brain, and problematic, unexamined assumptions concerning *how* language is processed and *how* that processing relates to brain activity, echoing influential comments by Poeppel and Embick (2005). Călinescu et al. comprehensively review functional neuroimaging on syntax, pointing out the inadequacy of many experimental paradigms in identifying what they claim to. Coopmans and Zaccarella discuss three concepts from syntactic theory: the distinction between competence and performance, the autonomy of syntax, and the abstract nature of syntactic representations, arguing that they are often incorrectly interpreted as applying to online language processing rather than as representational descriptions, or vice versa. Both papers assert that some of the confusion in neurolinguistics may stem from a misunderstanding or misapplication of concepts from linguistics. Uriagereka pushes at the edges of inquiry, suggesting a novel mathematical approach to decomposing syntactic features into an algebraic form. This decomposition may provide a greater opportunity to find a neural correlate of linguistic processing in the form of punctual and distributed representations than is currently evidenced in neurolinguistic research.

Conclusions

The papers in this volume are far from providing confident answers to the questions we posed in this Research Topic. However, they are inspiring in their breadth and their common cause of bringing to light the valuable and significant contributions of syntactic theory, when interpreted carefully, keeping in mind how syntax should be processed algorithmically in real-time, to neurobiology. They should provide a valuable starting point for new researchers looking to enter the field, either linguists who are curious about the brain or neurolinguists looking for theoretical grounding for their work.

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Moving away from lexicalism in psycho- and neuro-linguistics

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In standard models of language production or comprehension, the elements which are retrieved from memory and combined into a syntactic structure are "lemmas" or "lexical items." Such models implicitly take a "lexicalist" approach, which assumes that lexical items store meaning, syntax, and form together, that syntactic and lexical processes are distinct, and that syntactic structure does not extend below the word level. Across the last several decades, linguistic research examining a typologically diverse set of languages has provided strong evidence against this approach. These findings suggest that syntactic processes apply both above and below the "word" level, and that both meaning and form are partially determined by the syntactic context. This has significant implications for psychological and neurological models of language processing as well as for the way that we understand different types of aphasia and other language disorders. As a consequence of the lexicalist assumptions of these models, many kinds of sentences that speakers produce and comprehend—in a variety of languages, including English—are challenging for them to account for. Here we focus on language production as a case study. In order to move away from lexicalism in psycho- and neuro-linguistics, it is not enough to simply update the syntactic representations of words or phrases; the processing algorithms involved in language production are constrained by the lexicalist representations that they operate on, and thus also need to be reimagined. We provide an overview of the arguments against lexicalism, discuss how lexicalist assumptions are represented in models of language production, and examine the types of phenomena that they struggle to account for as a consequence. We also outline what a non-lexicalist alternative might look like, as a model that does not rely on a lemma representation, but instead represents that knowledge as separate mappings between (a) meaning and syntax and (b) syntax and form, with a single integrated stage for the retrieval and assembly of syntactic structure. By moving away from lexicalist assumptions, this kind of model provides better cross-linguistic coverage and aligns better with contemporary syntactic theory.

KEYWORDS

lexicalism, psycholinguistics, neurolinguistics, language production, lemma, aphasia

1. Introduction

For many years, people have been pondering the puzzle of how language is produced and comprehended; how do we get from a conceptual representation of what we want to say, to a series of articulatory gestures that make up speech or sign? When we perceive a series of such articulatory gestures, how do we interpret that signal to get the intended meaning? As an accident of history, many of the original researchers interested in this problem spoke European languages, particularly English and Dutch. For these researchers, the problem of language production should involve a few intermediary steps: once a concept has been generated, how do we retrieve the corresponding words from memory? After that, how do we build a syntactic structure from those words and put them into the correct linear order? In creating models to answer these questions, researchers were often making an unnoticed commitment about how language works, centered on a particular notion of wordhood. Dominant theories of syntax at the time—also largely developed based on European languages—assumed that "words" were the units of combination, and that everything happening below the word level belonged to a separate domain, morphology. In this kind of theory, the word acts as a bridge between meaning, syntax, and form. Psycholinguistic and neurolinguistic models incorporated this understanding of syntax and wordhood into both the representations and algorithms of those models. This is the lexicalist approach.

Lexicalism has been around for a long time in linguistics, and many of the foundational theories of syntax analyzed words as the minimal units in syntactic computations. Though the "Lexicalist Hypothesis" was first introduced in *Remarks on Nominalization* (Chomsky, 1970), lexicalism is not a single cohesive theory, but rather an approach taken by a variety of linguistic theories which rely on one or both of the following assumptions:

1. **Syntactic and morphological processes are different in kind:** Under this assumption, morphology (or other sub-word operations) and syntax (or other supra-word operations) are fundamentally different operations. Each has their own sets of atoms and rules of formation; syntactic rules operate over phrases and categories (NP, V, etc.), while morphological rules operate over roots, stems, and affixes. This establishes words as the "atoms" of syntax (Chomsky, 1970; Lapointe, 1980; Williams, 1981). Some interaction needs to exist between syntax and morphology, such as in verbal inflection, but lexicalist theories argue that the interaction functions in such a way that the two sets of rules and operations are not intermixed, and that only certain components can be referred to in both sets of rules.
2. **Lexical items include triads of sound, meaning, and syntax:** According to this assumption, everything which can be syntactically individuated has its own context-independent meaning and form. This creates a "triad," where each lexical item links a single meaning representation to a piece of syntax and a single form representation. The size and complexity of the piece of syntax can vary across theories; in some accounts, the syntactic component only contains a single syntactic terminal or a set of features (Jackendoff, 1975; Aronoff, 1976; Di Sciullo and Williams, 1987; Pollard and Sag, 1994), while in other accounts the syntactic component can be a "treelet" or "construction" that is morphosyntactically complex, thereby rejecting the first assumption above but retaining lexicalist properties (Kempen and Hoenkamp, 1987; Vosse and Kempen, 2000; Matchin and Hickok, 2020, among others).

In recent decades, much linguistic work, relying on a broader set of cross-linguistic data, has argued against both of these assumptions, suggesting that principles of word formation are the same as the principles of phrase or sentence formation, and that the word level does not always align with single units of meaning, syntax, or form. These non-lexicalist viewpoints have been developed into theories such as Distributed Morphology (Halle and Marantz, 1993), Nanosyntax (Starke, 2009), and the non-semiotic approach (Preminger, 2021). However, these developments have not been fully integrated into psychological and neurological models of language processing, leaving many phenomena across languages unaccounted for.

In this paper we argue that a non-lexicalist approach is needed for constructing more accurate models of language production. This paper does not elaborate greatly on the arguments against lexicalism within linguistic theory - much ink has already been spilt on this topic (Halle and Marantz, 1993; Harley, 2008; Starke, 2009; Siddiqi, 2010; Embick, 2015; Haspelmath, 2017; Jackendoff, 2017; Bruening, 2018, among others). Rather, we examine how lexicalism has influenced psycho- and neuro-linguistics, and discuss the consequences for the theories that make one or both of the lexicalist assumptions above. We focus on language production as a sort of case study, but we encourage readers to reflect on their own approaches using this case study as a model. The critiques of lexicalism and its effects in these models should apply to any kind of model or theory of language and language processing which makes either of these lexicalist assumptions, including sentence processing and single-word lexical processing, both in comprehension and in production.

The issues discussed here are partly related to linguistic diversity in model development. Using one's own language to generate models of language in general is not necessarily an issue—if you want to know how language in general is processed, a good place to start is to look into how one language is processed. However, a phenomenon which is deemed to be "exceptional" in one language—and thus exempt from the usual steps in linguistic processing—may be commonplace in other languages. Given the assumption that all languages utilize the same underlying cognitive processes, our models also need to account for those kinds of data.

The rest of the paper is composed of two main sections. In the first, we discuss how lexicalist assumptions are implemented in the language production literature, especially as they relate to the "lemma" representation, and how the models operate over those representations. We also elaborate on the kinds of data that these models struggle to account for, given their lexicalist assumptions. The second section discusses what an alternative might look like, as a non-lexicalist model of language production. To move away from lexicalism in models of language production, it is not enough to simply update the syntactic representations; it is also necessary to reconsider the algorithms involved in language production, because they are constrained by the lexicalist representations that they operate over. Instead of relying on a lemma representation, a non-lexicalist production model can represent stored linguistic knowledge as separate mappings between meaning and syntax, and syntax and form, such that meaning, syntax, and form may not line up with each other in a 1-to-1-to-1 fashion. Such a model can also account for prosodic computations that depend on meaning, syntax, and form information. Furthermore, we suggest that cognitive control mechanisms play an important role in resolving competition between the multiple information sources that influence the linearization of speech.

As we illustrate, non-lexicalist production models generate distinct predictions for aphasia and other acquired language disorders. By moving away from lexicalist assumptions, this kind of model provides better cross-linguistic coverage and aligns better with contemporary work in syntactic theory which has observed that syntactic and morphological processes cannot be distinct, that there are no good criteria to empirically define wordhood (Haspelmath, 2017), and that representations of meaning and form do not always align. However, it is important to recognize that the experimental literature in the lemma tradition has played a crucial role in psycho-and neuro-linguistics through its recognition of abstract syntactic representations independent of meaning and form. We are in complete sympathy with those models on this point, and we preserve this insight in the non-lexicalist architecture we propose here.

2. Lexicalist approaches in psycholinguistics

Lexicalist assumptions have played a central role in the development of models of language processing, either explicitly or implicitly. Many models of language production assume something like a lemma or lexical item, which functions as a stored triad of form, meaning, and syntax, also codifying a distinction between morphology and syntax. These models also create a division between lexical and syntactic processes, treating morphology as a different system from syntax. We discuss several models as examples, but these observations apply to any psycholinguistic or neurolinguistic theory which makes similar assumptions about the structure of linguistic knowledge. We introduce specific phenomena in several different languages, which are meant to represent a variety of phenomena across human languages. These phenomena are not isolated instances that can be treated as outliers, but rather common occurrences in human language that also need to be accounted for in models of language processing.

2.1. Lemmas and other lemma-like things

Many models of language production rely on the notion of "lemmas" (Kempen and Huijbers, 1983; Levelt, 1989; Bock, 1995; Levelt et al., 1999). According to the Levelt model, a lemma is a representation which stores syntactic information, and also points to a conceptual representation and a phonological form, bridging the Conceptual Stratum, Lemma Stratum, and Form Stratum. In this model, there is a lemma for every "lexical concept," and once a lemma has been selected for production, the lemma activates the phonological codes for each of its morphemes. These models commonly assume that the lemma is a terminal node in the syntactic structure (Levelt, 1992). Syntactic frames for these lemmas can specify how semantic arguments—such as "theme" or "recipient"—should be mapped onto syntactic relations - such as direct or indirect object (Levelt and Indefrey, 2000). Syntactic structure is built by combining multiple lemmas which have been retrieved from memory, according to their selectional restrictions and syntactic frames that are provided.

The diagram in Figure 1 of the lemma for the word "escorting" (from Levelt et al., 1999) illustrates how the lemma uniquely identifies a lexical concept in the Conceptual Stratum. The lemma has a number of "diacritic parameters" which need to be specified, including features such as number, tense, aspect, and person. These features may be prepared at the conceptual level or at the point of grammatical encoding. The lemma and its given features point to the phonological form of the stem *escort* and its suffix *-ing*, along with the metrical structure of the word. For morphologically complex words like *nationalize* and compounds like *afterthought*, the lemma model assumes a single simplex representation at the lemma stratum which maps to several form pieces in sequence at the form stratum (Roelofs et al., 1998). There are slight variations in the assumptions made by different lemma models of language production; for example, according to Levelt and Indefrey (2000), function words have their own lemma, while in the Consensus Model (Ferreira and Slevc, 2007), they do not. Some production models refer instead to "lexical items," but these are usually given similar attributes as lemmas and embody the same lexicalist assumptions.

2.1.1. Lemmas encode a distinction between lexical and syntactic processes

The lemma codifies a fundamental distinction between morphology and syntax. Morphologically complex words are taken to embody complexity in lexical representations and retrieval processes, rather than syntactic complexity. Because inflectional morphology and derivational morphology is stored within lemmas, and syntactic properties of the lemma are only represented by features obtained through indirect interaction, the lemma creates a "bottleneck" between morphology and syntax. For English, this might seem reasonable, but for languages with richer morphology and inflectional paradigms, the lemma becomes increasingly unwieldy. For example, in polysynthetic languages, a single word can be composed of many productive morphemes, representing complex meanings. In order to represent those words as lemmas, each lemma would have to correspond to very complex lexical concepts, with many redundant lemmas, to represent all of the possible morpheme combinations in that language; alternately, each lemma would have to incorporate a massive set of features in order to have a "complete" inflectional paradigm.

Along a similar vein, the idea that lemmas only exist for words and their inflections and derivations, reinforces the idea that it is only *complete* words that are stored in the lexicon, rather than pieces smaller or larger than a word. We can take as an illustration the commonly cited myth that "Eskimos have 150 words for snow," which has been debunked several times over (Martin, 1986; Pullum, 1989; Kaplan, 2003). As polysynthetic languages, Eskimoan languages such as Inuktitut have several main "snow" root morphemes (*aput*, "snow on the ground;" *qana*, "falling snow," *piqsirpoq*, "drifting snow;" *qimuqsuq*, "snowdrift") which can be combined productively with a wide array of other morphemes to create a massive number of words relating to snow: types of snow, quantities of snow, adjectival forms such as "snow-like," verbs involving snow, verbs where snow is the object, and so on. We could describe this situation by saying that Inuktitut has a tremendous number of "words" for snow and snow-like things, but this would be a bit like noting that English has a tremendous number of phrases or sentences about snow—it is simply not a very useful description of the language.

Because the lemma model assumes that morphological structure and syntactic structure is fundamentally different, and that derivational and inflectional morphology is stored within the lemma (and not built on-line like syntactic structure is), the individual morphemes within each word cannot exist independently of the lemmas that they appear in. Consequently, the lemma model has two options. One is to assume that each derived form in Inuktitut constitutes a separate lemma, and thus that there are 150+ different lemmas for each derived form of "snow;" this creates a great deal of redundancy, since each lemma would list the same root morpheme separately. The other option is to assume that there is a single lemma for *snowflake* stored with a massive inflectional paradigm that can generate all the derived forms that include the snowflake morpheme.

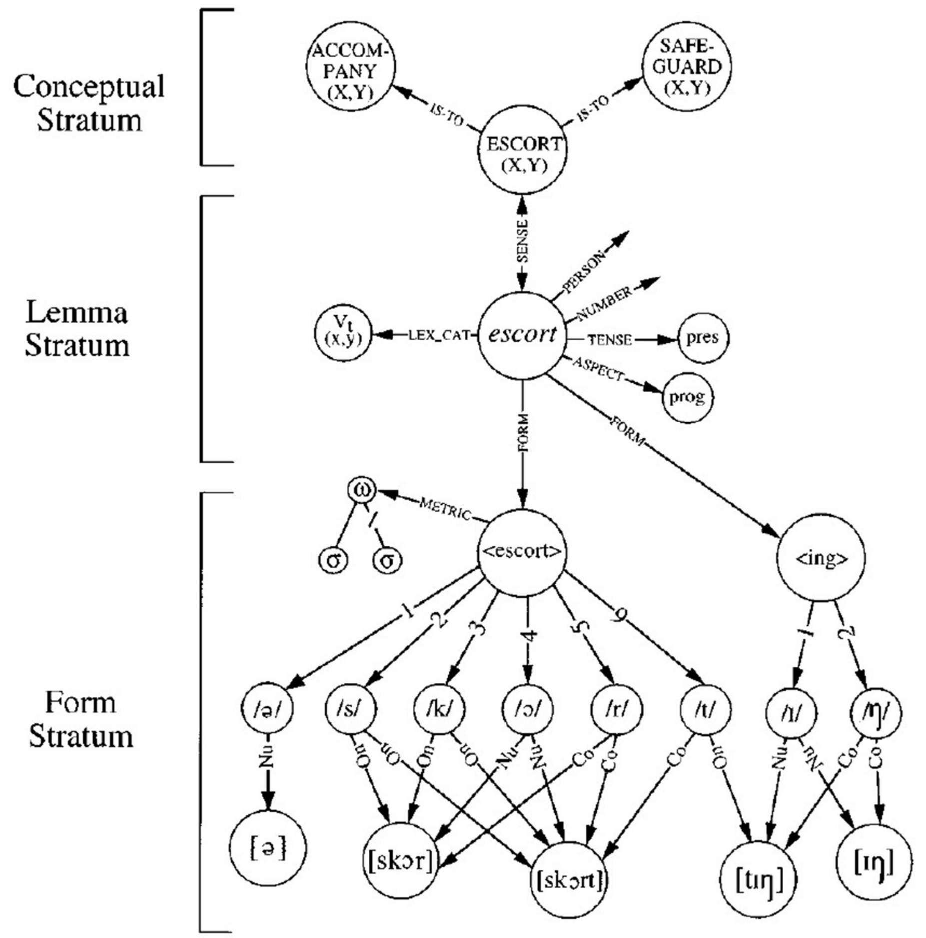

FIGURE 1
Lemma representation of the word "escorting," from Levelt et al. (1999), reproduced with permission.

This same dilemma would arise for every root in the language, of which there are thousands. For these languages, the lemma—as it is currently defined—is not a useful construct.

Let's look at a few examples from Inuktitut[1] to appreciate the challenges polysynthetic languages pose for lemma models of production (examples from Cook and Johns, 2009; Briggs et al., 2015):

(1) a. nivak -tuq
shovel.debris -PTCP.3S
"She shovels debris, old snow [out of the door]"

b. uqaalla -qattaq -tunga
say -often -PTCP.1S
"I say that sometimes"

c. havauti -tuq -ti -taq -niaq -tara
medicine -drink -cause -frequently -going.to -PTCP.1S/3S
"I'm going to give her medicine frequently"

1 These examples come from the Utkuhiksalingmiut dialect of Inuktitut, which is currently spoken in the Inuit communities in Gjoa Haven, Baker Lake, and formerly in the Black River area of Nunavut.

The sentence in (1a) is a good example of a case that the lemma model can handle with the same machinery used for English and Dutch inflectional morphology, as illustrated for "escorting" in Figure 1. The *nivak* lemma could simply be specified with inflection diacritics for mood, person and number, agreeing with the (null) subject. If we turn to the sentence in (1b), perhaps the lemma representation could remain simple as in (1a), and the complexity could be limited to the form level as the sequence of forms, *uqaalla*, *-qattaq*, and *-tunga*, similar to how the model represents compounds and other derived forms. However, since the lemma model assumes that each lemma corresponds to a single stored "lexical concept," this case would require assuming that speakers store atomic lexical concepts like "I say that sometimes." A case like (1c) appears more challenging yet to represent as a single inflected lemma. How might the lemma model try to represent the many different units used to generate this single complex word?

One possibility, following (1b) would be to assume that there is a single stored lexical concept that corresponds to the entire meaning "I'm going to give her medicine frequently," and thus a single corresponding lemma, with complexity at the form level only. This seems implausible. This would mean storing as separate full lexical concepts the meanings corresponding to every similarly-structured word that speakers produce (e.g., "I'm going to give her vitamins frequently)", and would put pressure on the theory to provide a

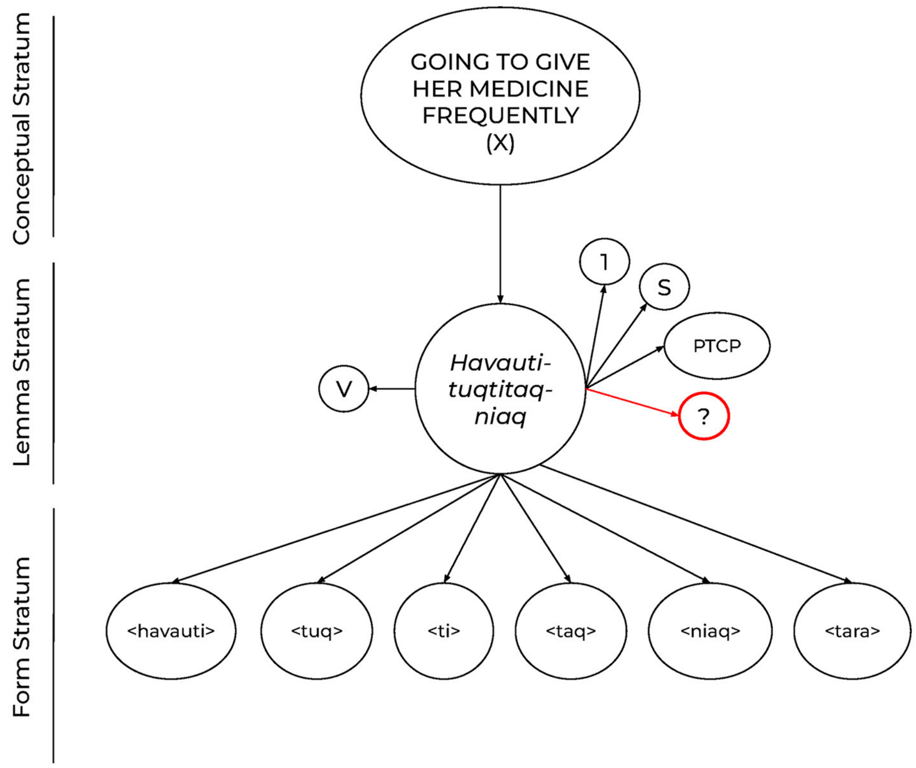

FIGURE 2
A possible lemma representation for the Inuktitut example in (1c), *havautituqtiniaqtara*, "I'm going to give her medicine frequently".

systematic account of how this multiplicity of lemmas containing productive derivational morphology was created in the first place.

An alternate approach to (1c) would be akin to the inflectional morphology case, to assume a core lemma for the lexical concept "medicine," and then generate the complex utterance in (1c) from a set of diacritics on the lemma, as illustrated in Figure 2. But this would lead to another question about what kinds of diacritic features could possibly represent each of those morphemes, especially if they would go unused in the majority of cases (the morpheme for "drink," *-tuq*, would appear relatively rarely, seemingly not enough to justify its status as a feature in the lemma representation, in contrast to features like tense or number), and considering that they can be used productively. Furthermore, the relationship between the morphemes within a lemma is only one of linear order, so this would mean that no non-linear structured relations between the elements of (1c) could be represented by the lemma. This would be problematic given the large body of evidence from polysynthetic languages for non-linear (hierarchical) relations between the elements within morphologically complex words. [2]

If one sticks with the core idea of the lemma model, that lemmas are defined such that a single lemma corresponds to a single lexical concept, intuitively the best solution to (1c) is to assume that the individual morphemes within the word like those for "medicine," "drink," and "frequently" have their own stored lemmas. This means giving up a view of production in which stand-alone words always correspond to stored lemmas, and instead adopting the non-lexicalist assumption that morphologically complex "words" can be constructed in the course of production in the same way that sentence structure is. Although the need for this move is most obvious in the case of the production of languages with rich morphology, assuming a processing model in which lemmas can be combined to form structured words provides a needed account of productive morphological word formation in languages like English or Dutch as well.

There is additional evidence that syntactic rules must be able to operate across the boundary between morphology and syntax, challenging the lexicalist notion of the "atomicity" of words, that words are the units of syntactic combination. As discussed by Noyer (1998), idiomatic collocations in Vietnamese are composed of several morphemes, which in some cases are syntactically separable, as shown in (2), where the collocations preserve their idiomatic interpretation when separated by other syntactic material (often used in Vietnamese for stylistic effect or affect).

2 There is a wide array of evidence that morphemes are hierarchically structured, both from lexicalist and non-lexicalist accounts. For example, the English word "unlockable," can either mean "able to be unlocked" or "not able to be locked;" the ambiguity in meaning can be analyzed as a structural ambiguity between [[un - lock] - able] and [un - [lock - able]]. The debate here is not whether morphemes are hierarchically structured, but whether that hierarchical structure is morphosyntactic or purely morphological in nature. Baker (1985) and other non-lexicalist approaches argue for the former, while lexicalist accounts argue for the latter. Morphemes only being linearly ordered is a more general issue for the lemma model, not just because of their lexicalist assumptions.

(2) a. Tôi xay nhà cửa → Tôi xay nhà xay cửa
I build house door → I build house build door
"I build a house"

b. Tôi không muốn đèn sách → Tôi không muốn đèn không muốn sách
I NEG want lamp book → I NEG want lamp NEG want book
"I do not want to study"

c. Tôi lo vườn tược → Tôi lo vườn lo tược
I care.for garden XX → I care.for garden care.for XX
"I take care of gardens"

According to the lemma model, these idiomatic collocations would need to constitute single lemmas with multiple morphemes. Each collocation would correspond to a single lexical concept because of their idiosyncratic meanings—and in some cases, parts with unavailable meanings of their own (indicated by "XX" in the gloss). Furthermore, in (2b), though đèn ("lamp") and sách ("book") are nouns individually, when used together they function as a verb; because syntactic category is a property of lemmas and not morphemes, this provides further evidence that they must constitute a single lemma. However, if a sequence like đèn sách corresponded to a single lemma with separate pieces at the form level only, then the two pieces of the collocation could only appear adjacently and would not be syntactically separable, no different from *escort* and *-ing* in Figure 1.

Some work in the lemma tradition has tried to develop an alternative approach to deal with phrasal idioms. Cutting and Bock (1997) and Sprenger et al. (2006) argue that idioms have a "hybrid" representation, where there is a lexical concept node or "superlemma" for the idiom which also activates the lemmas of its constituents (i.e., the superlemma for "kick the bucket" would activate the simple lemmas for "kick" and "bucket"). One of the key assumptions of these accounts is that each of the constituents of the idiom must have its own lemma representation that can be activated. Because all lemmas must have an associated lexical concept, this assumes that every idiom would have a literal interpretation which is overridden by the idiomatic interpretation. However, for the Vietnamese idiomatic collocations, and example (2c) in particular, this claim would be problematic. The morpheme tược has no interpretation outside of the idiomatic collocation, so it could not correspond to a lexical concept independent from the idiom; thus, there could not be a tược lemma which could be activated. Furthermore, Kuiper et al. (2007) argues that the superlemma specifies only phrasal functions between simple lemmas (constituting a VP or NP, for example), rather than sub-word pieces or a single syntactic category. This would be a problem for the đèn sách ("study") example, where two nouns are compounded to form a verb; a VP requires a verb head, but neither element would be able to serve that function (in contrast to English phrasal idioms like the VP "kick the bucket," or the NP "kit and caboodle").

These examples challenge one of the key assumptions of the lexicalist approach, that syntax and morphology are separate operations that cannot interact. In order to account for these kinds of examples, the only solution would be to assume instead that the đèn and sách morphemes within the "study" lemma are themselves syntactic objects that can interact with the syntactic structure. This means giving up a view of syntactic structure where words or lemmas are the units of combination, and instead adopting the non-lexicalist view that morphology and syntax are part of the same system. The evidence from Inuktitut and Vietnamese indicates that, not only do we need to move away from a view of production in which stored lemmas correspond to words, but we also need to give up the idea that the units of language production are syntactically atomic by definition.

2.1.2. Lemmas function as a stored triad

The lemma is defined as grouping together form, meaning, and syntax, creating the "triad." The lemma maps between meaning, syntax, and form in a "symmetrical" way, where for every element that is syntactically individuated, it is also individuated in terms of meaning and form, not dependent on other lemmas or the syntactic context. Even if the phonological form is not stored within the lemma itself, the mapping between lemma and form is deterministic and context-independent. If we make this assumption, we would not expect there to be cases where meaning, syntax, and form would be mapped to one another in more complicated ways, or instances where the syntactic context would impact the form or meaning of individual words.

One place in which the phonological form seems to be conditioned by the broader syntactic context that it occurs in is suppletion. Existing models have a way to account for some kinds of suppletion, such as what is seen for a few English verbs, based on tense (*go* ~ *went*) and agreement with the subject (*is* ~ *am*). However, it is harder for this kind of model to account for suppletion based on a larger piece of syntax, where the form is not determined by a single syntactic object or a limited set of features, but by the larger syntactic context. For example, Hiaki[3] exhibits suppletion for some verbs with singular and plural subjects, as well as singular and plural objects (examples from Harley, 2014):

(3)
a. vuite ~ tenne — *run.sg* ~ *run.pl*
b. siika ~ saka — *go.sg* ~ *go.pl*
c. weama ~ rehte — *wander.sg* ~ *wander.pl*
d. kivake ~ kiime — *enter.sg* ~ *enter.pl*
e. vo'e ~ to'e — *lie.sg* ~ *lie.pl*
f. weye ~ kaate — *walk.sg* ~ *walk.pl*
g. me'a ~ sua — *kill.sg**Obj*** ~ *kill.pl**Obj***

For the English verb *escorting* above, the diacritics for the person and number of the subject help to determine the inflection on the verb for agreement; for the Hiaki verbs that exhibit suppletion based on the number of the subject or the object, as shown in 3, there would need to be two diacritics for number, one for the subject and one for the object, as indicated in Figure 3. One issue for this kind of representation is that one or both of these sets of diacritics would always be redundant, especially because Hiaki does not inflect regular verbs—those that do not have suppletive forms—for person or number [the form of the regular verb *aache* ("laugh") is the same for all subjects; Sánchez et al. (2017)].

3 Hiaki (also referred to as *Yaqui* or *Yoeme*) is an Uto-Aztecan language spoken in the states of Arizona (USA) and Sonora (Mexico).

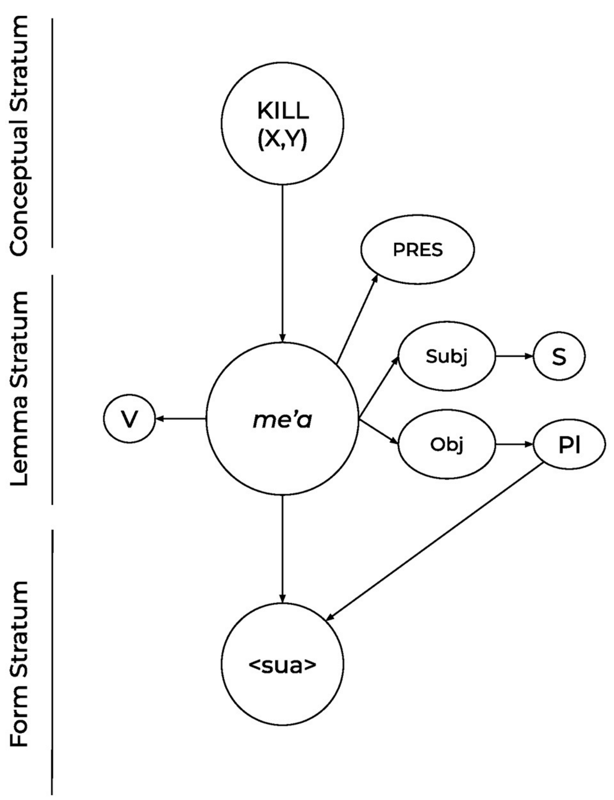

FIGURE 3
A possible lemma representation for the Hiaki suppletive verb *sua*, "kill.plObj." The "Subj" and "Obj" diacritics would indicate the number feature on the subject and object of the sentence, but they would often be redundant, given that regular verbs in Hiaki do not inflect for person or number.

Verb-object idioms provide evidence that the meaning of a syntactic unit can also be dependent on its morphosyntactic context. Examples such as those in (4) indicate that the meaning of verbs like *pass*, *take*, *get*, and *kill* can be dependent on the semantic content of its object, while remaining indifferent to that of its subject. Although many architectures treat idioms as exceptions, these kinds of examples are very common, and are used in a variety of registers. The strong and systematic dependence of the verb's meaning on the object in these cases make them unlike simple cases of lexical ambiguity.

(4) a. Pass: *pass a test, pass a law, pass a kidney stone, pass the hat*
 b. Take: *take a photo, take a nap, take a bus, take a chance*
 c. Get: *get a package, get the idea, get the check, get scared*
 d. Kill: *kill a bottle, kill an evening, kill the clock, kill the music*

If the meaning of each verb was uniquely specified in the lexicon, with no context-dependent interpretations, we would not expect any of these verb-object idioms to emerge with these idiosyncratic meanings. It is not clear that the lemma model can explain this phenomena simply by stating that these verbs are ones that are semantically "light" or "bleached," or underspecified for meaning, because the intended meaning of each verb phrase is clear and specific. In these cases, and in many other cases not listed here, the meaning of the verb is determined by its morphosyntactic context.

One could interpret these cases as homophony, such that there would be multiple lemmas which are pronounced as "take" that correspond to different lexical concepts (one for *steal*, one for *photograph*, one for *sleep*, one for *ride*, and so on). However, on a homophony account, it would be a coincidence that all the lemmas pronounced as "take" have the same irregular past-tense form "took." One could also interpret these cases as polysemy, but this would require an additional mechanism in the conceptual domain to link very different concepts to the same lemma, which would be an issue if lemmas are meant to correspond to single lexical concepts.

Another possibility would be to treat these as idioms with a "hybrid" representation, as proposed by Cutting and Bock (1997) and Sprenger et al. (2006), where the superlemma or lexical-conceptual representation of the idiom "take a nap" would activate the lemmas for *take* and *nap*, so the idiosyncratic meaning would be associated not with the *take* lemma itself, but rather with the superlemma. This account would suggest—contrary to the lexicalist approach—that a single conceptual unit can be mapped to a syntactic complex, and not just to a single syntactic atom. Furthermore, this also suggests that stored linguistic representations can be syntactically complex, involving both morphological and syntactic structure. We argue that both of these are important steps in the right direction, though we discuss the advantages and disadvantages of "treelet-based" approaches of this type in more detail in Section 2.1.4.

To summarize, lemmas are a manifestation of both of the lexicalist assumptions discussed above: they codify a distinction between syntax and morphology, and establish themselves as a stored "triad" of form, syntax, and meaning. As a result, there is a large amount of data that the lemma will struggle to model, including (but not limited to) inflection and morphological structure, suppletion, and idioms, phenomena which are fairly widespread throughout human languages. These phenomena suggest that syntax and morphology need to be able to interact fully, not just by sharing a limited set of features, and that the form and meaning of a syntactic object is partially determined by the syntactic context, not just by the syntactic object itself.

2.1.3. Incrementality and lexical units

A central concern for models of language production, going back over a century, is incrementality: how much of the preverbal message and linguistic encoding is planned before the speaker starts talking? If not all of it is planned in advance, how can speakers ensure that all the linguistic dependencies and word order requirements of the language are satisfied? Over the years, one common suggestion of highly incremental production models is that both preverbal and syntactic representations can be planned and updated in "lexically sized units," as proposed by Dell et al. (2008) and Brown-Schmidt and Konopka (2015). However, it is often not explicitly recognized how crucially these planning models thus depend on lexicalist assumptions about the units which are being incremented over. The reason is that an assumed one-to-one mapping from meaning to syntax to form makes it such that each increment of planning at one level can be matched by exactly one increment at the other levels. Without this assumption, there is no reason to think that the correct selection of a unit at the phonological level could be done by looking at a single unit at the meaning or syntax level, which is what maximal incrementality would require.

The cross-linguistic examples above that challenged the one-to-one mapping can be used to illustrate the parallel issues for lexically-based incremental production models. If a lexical unit corresponds to a single unit of meaning, then a fully incremental model would struggle to produce the two pieces of a Vietnamese idiomatic collocation in different, non-contiguous parts of a sentence. If the lexical unit corresponds to a single unit of syntax, then the two pieces of the idiomatic collocation would have to be separate units (as they are syntactically separable), and thus the incremental model would struggle to generate parts of the collocations that do not have independent interpretations, such as in (2c). If a lexical unit corresponded to the phonological word, that would suggest that a whole sentence in Inuktitut would be represented as a single lexical unit, again ignoring the productivity of morphology in polysynthetic languages. These incremental models would also struggle if the lexical units correspond to syntactic units but the meaning and form are determined solely by the lexical unit itself, for the same reasons discussed above for Hiaki verb suppletion and English verb-object idioms. For example, for the Hiaki verbs which exhibit suppletion based on the number of the object, such as *me'a* ∼ *sua* ("kill"), a fully incremental model would retrieve the meaning and syntax for "kill" correctly, but could not correctly condition its phonological wordform on the number of the object because at the time that the verb was being produced, the following object would not have been planned yet.

2.1.4. Treelet-based approaches — A step in the right direction

Many models of language production have taken steps to provide a more detailed account of the syntactic representation of lexical items, especially in regard to the separation of morphology and syntax in the representation of words. For example, Kempen and Hoenkamp (1987), Vosse and Kempen (2000), Ferreira (2013), and Matchin and Hickok (2020) (among others) propose models where the syntax of lexical items are represented as lexicalized "elementary trees" or "treelets." These models allow for the syntactic properties of a lexical item—such as argument structure—to be represented as syntactic structure, rather than a limited set of features or as sentence frames. Because the treelets are composed *via* syntactic rules, and then undergo a process of lexicalization in order to be stored as treelets, syntactic and lexical representations are thus not definitionally distinct, thereby rejecting the first lexicalist assumption, that syntax and morphology are separate systems that cannot interact. As long as the tree-based model assumes a syntactic theory which can accommodate the kinds of phenomena described above, it will be able to represent them as treelets. One could easily adopt a non-lexicalist theory of syntax, where even a single treelet could involve highly complex morphological structure, as is needed for Inuktitut and other polysynthetic languages, and for the structure of idioms, while still using the same basic operations and preserving the same architecture of the processing model.

However, these models are also clear examples of why it is insufficient to simply update the syntactic representations of the treelets without also reconsidering the criteria for lexicalization, and how the meaning and form of the resulting treelets are represented. These are all lexicalist approaches in that treelets correspond to stand-alone words or phrases, rather than pieces of syntax that are smaller than stand-alone words. Meaning and form are only specified for treelets, in a context-independent way, so the triad persists. Here, Inuktitut words pose the same kind of issue as they did for lemmas; a treelet would need to be stored in the lexicon for each possible stand-alone word in the language, some of which would constitute entire sentences. If these models were to argue that the treelets can be smaller than a stand-alone word in order to account for this data, then these models could not be considered fully lexicalist; however, they would still struggle to capture phenomena which are beyond the triad, because meaning and form would be specified for most treelets. Hiaki verbs that exhibit suppletion based on the number of the subject or object are still problematic, because there would need to be separate treelets for the same verb depending on the number feature of the subject or object. In addition, for treelet-based models which assume that the treelets are "atomic" in the sense that their sub-parts cannot participate directly in the syntactic structure outside of the treelet, they will struggle with Vietnamese idiomatic collocations and other similar phenomena as well.

More broadly, we agree that storage and retrieval of composed structures may turn out to be a central property of language processing, but they should not be defined in the lexical representations of words. The intuition captured by these treelets might be better understood not as a *representation* but perhaps as a byproduct of the implementation in a highly adaptable neural system. Furthermore, we see no reason that this property should be restricted to things at the "word" level; it should apply equally to phrases as well as sub-word pieces.

2.1.5. Language-specific optimization

So far in this section, we have argued against the claim that the system of language production requires lexical knowledge to be formatted in terms of lemmas or lexical units as an organizing principle. However, for things that do have a 1-to-1-to-1 mapping between meaning, syntax, and form (where a single syntactic object has a consistent meaning and form across a variety of contexts), it would be entirely plausible that lemmas—or something like them—could arise as a byproduct of language-specific optimization, where it would be faster or more efficient to represent meaning, syntax, and form in that way, even if it is not an architectural principle. In these cases, it is possible that the translations which are performed for that word can treat the word as if it were atomic (i.e., the calculation to determine the form for the word does not need to refer to any other elements in the syntactic context), as is suggested by the lemma model. This kind of symmetry might occur more often in some languages, so linguistic behavior may appear to be more "lemma-like" than it would for other languages. To be clear, this would be a consequence of optimization at the *implementation* level, rather than the *representation* or *algorithm* level (Marr, 2010); it should be the case that speakers of all languages have the same underlying mechanisms which can become specialized depending on the frequency and complexity of processes that are involved in the language.

The possibility of "lemmatization" may not hold for every piece of syntax in a single language, even in English, but it is an interesting empirical question which is only made possible under a non-lexicalist approach—under what circumstances would a "lemma" be formed, if at all? It seems entirely plausible that a neural system which is searching to optimize and reduce resource use wherever possible would store frequently used linguistic objects in some way, and it is possible that something like a lemma could arise for some items in a language. A central commitment of lexicalist theories is that there is a principled divide between what kinds of representations can be stored in the lexicon and what has to be generated online. In contrast, non-lexicalist approaches that do not assume such a divide are free to predict that frequently generated relations *of any kind* could be stored, if this would facilitate future production operations. This could include commonly-used phrases (such as "kick the ball" or "walk the dog"), Multi-Word Expressions (as discussed by Sag et al., 2002; Bhattasali et al., 2019), or groups of words with high transition probabilities. The same considerations that apply to whether or not a complex word like "nationalize" is stored will also apply to whether or not a common phrase is stored. Depending on the properties of a particular language, storage of different sized pieces may optimize production, allowing wide variation cross-linguistically in the size of the stored pieces even if the underlying grammatical architecture is assumed to be the same.

2.2. Division between lexical and syntactic processes

As we touched on in the discussion of incrementality above, assumptions about processing algorithms are deeply intertwined with assumptions about the units of representation. In the case of language production, the lexicalist assumptions that characterized the lemma units led to models which made a fundamental division between the process of lexical selection and the process of syntactic structure building. Much of the same data discussed above presents a clear challenge for models that work this way. This means that moving to a non-lexicalist production model is not just a matter of updating the representation of stored linguistic knowledge.

In the Levelt and Indefrey (2000) model, the lexical concepts for the sentence are first selected, and then the corresponding lemmas are retrieved from memory. The syntactic structure is built incrementally as lemmas are retrieved, according to the syntactic frames of each lemma, and subsequent lemmas are inserted into the syntactic structure. For example, to produce the sentence "Maria kicked the ball," the lemmas for "Maria," "kick," "the," and "ball" would be retrieved. The verb "kick" has a syntactic frame which specifies its arguments and the thematic roles that they have in the sentence, so "Maria" would be inserted into the subject position because she is the agent, and "the ball" would be inserted into the object position because it is the patient. In this way, every lemma (except the first one which initiated the structure building) is inserted into a "slot" in the syntactic structure as it is being built. Once the syntactic structure has been built, the morphophonological code for each of the lemmas is retrieved, followed by phonetic processes and articulation.

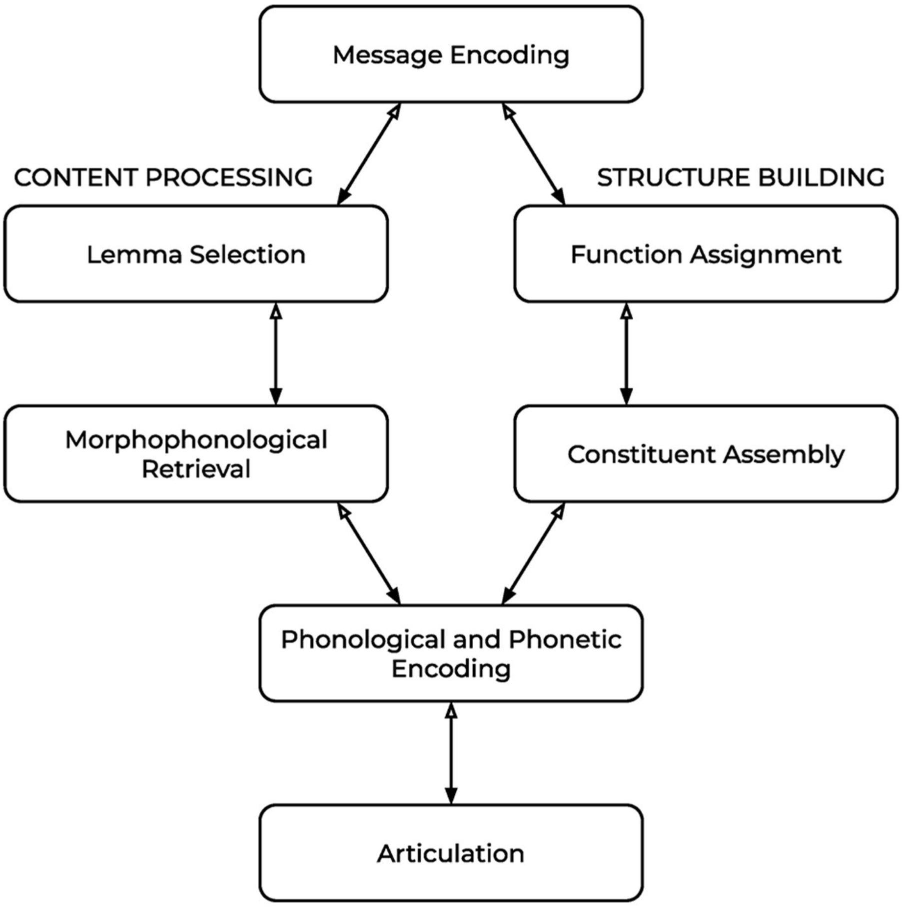

FIGURE 4
Model of sentence production according to Ferreira and Slevc (2007).

However, idiomatic collocations in Vietnamese are difficult to explain in a model in which lemma selection and syntactic structure building are separate processes, because they demonstrate that syntax needs to operate across the boundary between syntax and morphology. Because each idiomatic collocation corresponds to a single lexical concept, it would be represented by a single lemma. In the Vietnamese sentence for "I do not want to study," in example (2b), the *want* lemma would be retrieved, and because the *study* lemma is its complement, it would be inserted into the syntactic structure as a single lemma with two morphemes; the two pieces of the collocation would only appear adjacently. In order to have them appear separately, one would either have to argue that there is an additional step of post-insertion movement which allows the pieces to appear in separate positions in the structure, even though lemmas are treated as being syntactically atomic, or that the idiomatic collocation corresponds to two lemmas that are retrieved independently and inserted into their respective positions in the syntax—in which case, the idiosyncratic meaning could not arise without the involvement of an additional mechanism. Another possibility is that there are two lemmas for the same idiomatic collocation, one for when the two pieces are adjacent to each other, and one when they are not, each with a different syntactic frame to specify how the structure is built around it; again, this would not explain how both lemmas would get the same idiosyncratic meaning. None of these possibilities are available in the current lemma model.

Looking now at the the Consensus Model proposed by Ferreira and Slevc (2007), shown in Figure 4, which likewise operates over lemmas, the main difference in this model is that the process of lemma selection and morphophonological retrieval ("content processing") is done in isolation from the syntactic composition ("structure building"), as two separate subprocesses. As a consequence, the building of the syntactic structure is driven by conceptual properties and thematic function rather than the selectional restrictions of individual elements in the syntax. To produce the sentence "Maria kicked the ball," the message would first be encoded in terms of semantic meaning—the entities and concepts that are involved in the sentence—and relational meaning—how those entities relate to one another in the sentence, as agents and patients, and so on. On the "content" side, the lemmas for "Mary," "kick," and "ball" would be selected (function words and morphemes do not have their own lemmas), while on the "structure" side, the syntactic structure would be created for the sentence. When the morphophonological code for each lemma has been retrieved, they would be inserted into their position in the syntax (though the authors concede that the problem of how exactly those forms are inserted into the correct position does not currently have a solution).

This division between structure building and content processing poses several problems for the cross-linguistic phenomena reviewed here. Firstly, this model would have trouble generating Hiaki verb suppletion conditioned on the object, because morphophonological retrieval happens in isolation from constituent assembly; the "relational meaning" of the object (how the object relates to the other entities in the sentence, as the agent or patient of the verb) would be available, as would the conceptual representation of the object as singular or plural, but the syntactic structure and syntactic features would not be.[4] At the point of morphophonological retrieval, none of those features would be accessible to the *me'a* lemma.

The production of Hiaki suppletion could be accomplished if there are connections between "lemma selection" and "structure building," and between "morphophonological retrieval" and "constitutent assembly," as is assumed in Eberhard et al. (2005). This framework allows for syntactic structure building to have an influence on a lemma's morphophonological form, assuming that there is a mechanism by which the features of the object lemma could be indirectly shared with the verb lemma. However, for both the Consensus model and the Eberhard et al. (2005) model, separation between structure and content (or the syntax and the lexicon) will cause problems in other cases where the lemmas would need to interact with the syntax beyond just sharing features, such as in the Vietnamese idiomatic collocations, where elements of the collocation can be syntactically separated.

In this discussion so far, a paradoxical problem seems to arise relating to the order of operations. In the discussion of the Levelt and Indefrey model, we argued that there will be issues if lemmas are inserted into a syntactic structure which was built *before* they were retrieved, in order to account for the production of Vietnamese idiomatic collocations. In the discussion of the Consensus Model, we argued that the syntactic structure should not be built *at the same time as*—but separately from—the lemma retrieval process, in order to account for the production of Hiaki verb suppletion conditioned on the plurality of the object, as well as instances where "lexical items" need to interact with syntax beyond sharing a limited set of features. It also should not be the case that the syntactic structure is built entirely *after* the lemma retrieval process, or there may be issues with verbal arguments not being satisfied.[5] Part of this problem stems from the ordering issue—at what point the lemmas are retrieved relative to the building of the syntactic structure—but also due to the commitment to the lemma as an atomic unit. These issues would not be resolved by adopting a tree-based approach, which uses syntactically-complex treelets, but assumes a similar model architecture. The non-lexicalist

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4 It is important to note here that this is about the syntactic feature of number, not the semantic feature. Something being semantically plural does not necessitate that it is syntactically plural, and vice versa. For example, "scissors" is syntactically plural, while being semantically singular, while "furniture" is syntactically singular while being semantically plural. In the cases where there is a mismatch between the syntactic and semantic features, agreement always occurs with the syntactic features, not the semantic ones. Furthermore, if there is a mismatch in conceptual number features but not syntactic number features, the sentence will be grammatical, even if it is semantically odd. Some verbs like "juggle" seem to require a plural object at a conceptual level (# *John juggled the task*), but the sentence is still syntactically well-formed (contrast with a sentence like "the furniture are in the living room," which involves agreement mismatch). As a consequence of this, it cannot be the case that the features necessary for agreement or argument structure are necessarily available at a purely conceptual level.

5 If the syntactic structure is built only after the lemmas have been retrieved, and the speaker wants to use a verb such as *devour*, they may not have selected the lemma for the object even if one would be required, given that the syntactic requirements of the verb may not correspond to semantic or conceptual arguments. Because the model is serial, there would be no way to "go back" and retrieve the missing lemma.

solution to this conundrum is that syntactic structure building and the retrieval and insertion of morphemes is a fully interactive process. There should be no stage at which the processes occur in isolation. Thus, rather than treating these as two separate processes, in the non-lexicalist approach we can treat them as a single unified process of syntactic structure building.

2.3. In summary

The evidence raised in this section, coming from a set of typologically diverse languages, demonstrates that the lexicalist approach is problematic not just in syntactic theory, but also for models of language production. Lemmas—and other things like them—encode lexicalist assumptions about the organization of the language system, either implicitly or explicitly, and the models which use them encode those assumptions in their algorithms. As a result, there are many phenomena that those models of language production will struggle to account for, not just in Inuktitut, Vietnamese, and Hiaki, but in languages like English and Dutch as well. The kind of model change that these considerations require cannot be satisfied by updating the terminology; the representations and algorithms involved in the model need to be fundamentally different, operating over different kinds of units and performing different calculations.

3. Moving away from lexicalism

As we move away from a lexicalist model to a non-lexicalist one, many questions arise. What are the units over which the model operates, if they are not lemmas or words? What other processes must be incorporated into the model if there is no representation which directly links meaning, syntax, and form? How are the different components—meaning, syntax, and form—retrieved, and when? How are they able to map to one another? In this section, we outline one possibility for a non-lexicalist model of language production, and discuss the implications of such a model for how we view language processing and language disorders such as aphasia.

3.1. The non-lexicalist model of language production

The data presented above suggest that there is no split between morphology (or other sub-word operations) and syntax (or other supra-word operations), and that there are many cases of stored linguistic knowledge which cannot be encoded as triads of meaning, syntax, and form. In our current approach, we assume instead that linguistic knowledge includes sets of syntactic atoms, sets of mapping rules between syntactic units and meaning units, and sets of mapping rules between syntactic units and form units (Preminger, 2021). The syntactic terminals are fully abstract, meaning that they have no form or meaning themselves; both their meaning and form are conditioned by their context within the syntactic structure. The two sets of mappings may not necessarily be "symmetrical," in that for a single component of meaning which maps to a piece of syntax (however complex), that piece of syntax may not map to a single form segment; conversely, for a single form segment which maps to a piece of syntax, it may not correspond to a single component of meaning, as illustrated in Figure 5. Furthermore, it is also possible in this model for a piece of syntax to have no mapping to meaning (for example, the expletive *it* in a sentence like "it is raining" has no possible referent) or no mapping to form (such as phonologically null elements).

As a concrete example of this notion of asymmetricality, we can refer to the phrase "went off," as in "the alarm went off." In this example, the meaning components would be something like "ring" and "past." The "past" meaning component maps to a [+PAST] morpheme, and the "ring" meaning component maps to two morphemes, [GO] and [OFF]. On the form side, given their syntactic configuration, [+PAST] and [GO] map together to the form of *went*, even though they correspond to separate meaning components, while [OFF] alone maps to the form *off*, even though it did not constitute its own meaning component. In a strict triadic (symmetrical) view, a single segment of form can only correspond to a piece of syntax which corresponds to a single meaning component. This view would be especially problematic for *off* in this case, because it does not have the same meaning in this context as it does independently (either "not on top of" or "not operating," neither of which would apply for an alarm that is actively ringing). Symmetrical mappings are still possible in the non-lexicalist model ("alarm" has a single meaning component, a single piece of syntax, and a single form segment), but this would not be a requirement imposed by the language system.

Moving away from lexicalism resolves many of the issues discussed in Section 2. Inuktitut words can be composed of many morphemes which are arranged hierarchically, allowing them to be both structured and fully productive; the morphemes within Vietnamese idiomatic collocations can participate in the syntactic structure because lexical and syntactic processes are not distinct; the form of suppletive verbs in Hiaki can be determined based on a larger context, including the number feature of the subject or object; and because there are distinct representations of meaning, syntax, and form, and the mappings between them can be calculated based on a larger context, the variability in the meaning of "pass," "take," "get," or "kill" can be partially determined by their object.

In the model that we outline here—discussed in more detail in Krauska and Lau (in prep.)—language production involves a process of mapping a message to sets of syntactic units, which are then mapped to units of form. The two sets of mappings can be represented not in a deterministic way, but rather in a more probabilistic format, as a calculation over larger or smaller pieces of syntax. This model is non-lexicalist because the mechanisms which generate the syntactic structure make no distinctions between processes that apply above or below the word level, and there is no point at which meaning, syntax, and form are stored together as a single atomic representation. Each stage in the model is a translation between different kinds of data structures. The "message" integrates different components of non-linguistic cognition, including memory, sensory information, social dynamics and discourse information, theory of mind, and information structure. Translating that message into a syntactic structure means re-encoding the information into a format that is specifically linguistic, involving syntactic properties and relations that may not be transparently related to the intended message.[6] The hierarchical structure of syntax, in turn, must be translated into

6 For example, in the sentence "it rained," the expletive *it* does not correspond to an entity involved in the intended message, but is inserted due to the syntactic properties of English requiring sentences to have a subject.

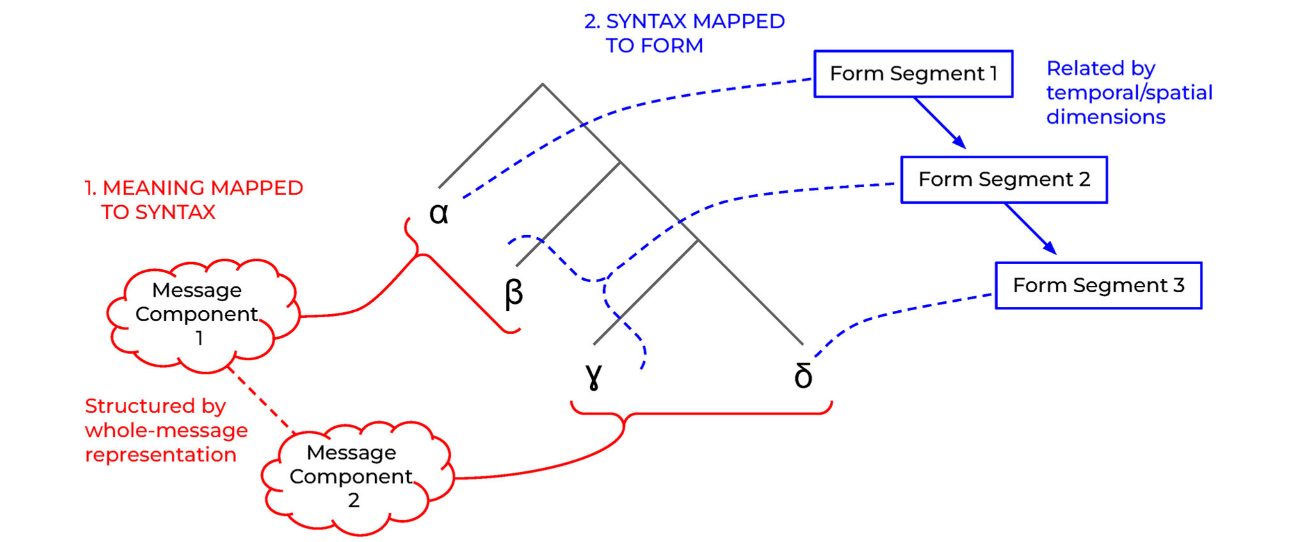

FIGURE 5
An illustration of the non-lexicalist approach, with separate mappings from (1) meaning to syntax and (2) syntax to form.

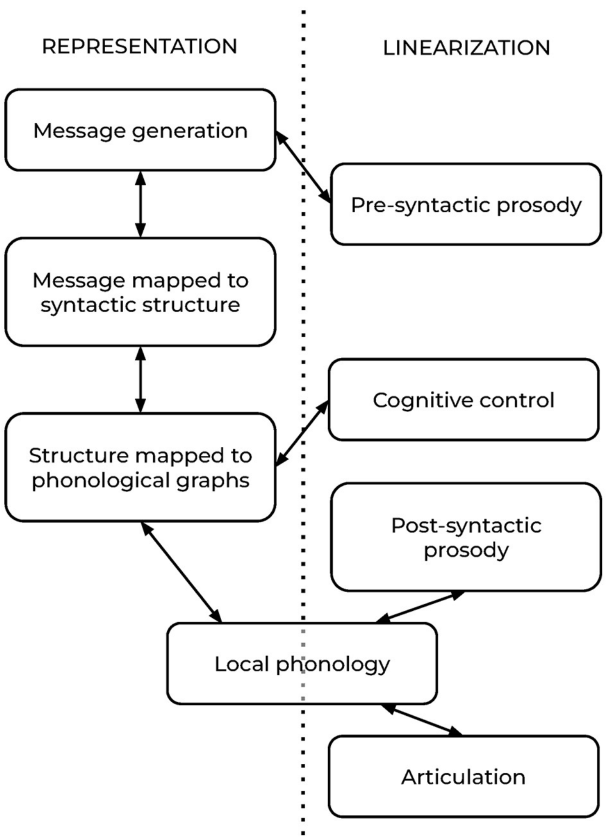

FIGURE 6
A non-lexicalist model of language production.

a series of temporally ordered articulatory gestures in order to be uttered as spoken or signed language.

The mechanisms in this model can be divided into two groups, as shown in Figure 6. The first is responsible for generating relational representations—conceptual representations, syntactic representations, and phonological (or other form) representations—and translating between them, then maintaining them in working memory, predominantly through circuits in the left temporal lobe. The second set of mechanisms, localized in the left frontal lobe, exert influence on the translations between representations and work to organize those representations into a linear (temporal) order. One additional feature of note in this model is that prosodic computations are split into separate pre-syntactic and post-syntactic stages. Prosody is determined by a combination of linguistic and non-linguistic factors; for example, contrastive focus is in part determined based on the speaker's knowledge of the common ground and theory of mind for other discourse participants; heavy NP shift and stress clash in double object constructions is created by the stress that different phrases may carry, which is lexically specified; the choice between rising question intonation and lowering declarative intonation is determined by the speaker's goals in the discourse. A natural solution to the diversity of features that enter into the prosodic calculation is to posit that it is accomplished in two stages, one calculated pre-syntactically, before any syntactic information is available, and another which must be calculated post-syntactically, perhaps after specific phonological information has become available.

Here we briefly summarize each component of the model to illustrate how the production process can work in the absence of traditional lexical items:

1. **Message generation:** Many different sources of information are consolidated into a message, including conceptual representations for the entities involved in the sentence, event structure, thematic roles, and information structure. This is message is "language-constrained" in that much of the information determining the message is not uniquely linguistic, but it also cannot be purely conceptual, because it must be partially determined by how the message is mapped to syntactic structure and which features in that language are grammatically encoded. For example, languages such as Turkish require "evidentiality" to be grammatically encoded; the grammatical form of a sentence must indicate whether the speaker personally witnessed the event or if the

information is second-hand, in contrast to English, where expressing such information is optional. This means that facts about linguistic form play a role in constraining the necessary content of the message to be expressed (Slobin, 1996). The non-lexicalist model suggested here allows linguistic form to influence the message by assuming interactivity between the message generation process and the subsequent process of mapping that message to syntactic structure. The message cannot be generated without some reference to the syntactic structure, and in turn, the syntactic structure cannot be generated without reference to the message.

2. **Message mapped to syntactic structure:** The next computation we consider is the generation of the syntactic structure, mapping the units of meaning onto pieces of syntax. The syntactic structure is a uniquely linguistic data type, involving a specific kind of hierarchical structure and other idiosyncratic properties. As just noted, this process is fully interactive with the message generation stage in order to produce the correct components of the message as required by the syntax. In contrast to the lexicalist approach, the pieces of syntax that are mapped to each unit of meaning in this model can be as small as a single morpheme, or as large as an entire phrase or sentence. There is no architectural constraint on the size or structure of the pieces of syntax which can correspond to a single unit of meaning. Another key non-lexicalist feature of this mechanism is that there is not a separate stage before, during, or after this one where "lexical items" are retrieved from memory independently from the syntactic structure building processes they participate in. In this model, the process of retrieving stored pieces of syntactic structure is integrated with the generation of novel syntactic structures, performed at the same time by the same mechanism, following the same set of syntactic principles.
3. **Pre-syntactic prosody:** Once the message has been generated, the speaker can know some things about the form that the utterance will take, even without having yet computed the full syntactic structure or phonological form. Message elements such as whether the utterance is a question or a declarative, as well as the social dynamics and discourse conditions involved, are often reflected in the prosodic structure of the utterance. For example, in English, if an utterance is a question, it will often exhibit both wh-movement (a syntactic phenomenon) as well as question prosody, which often involves rising pitch (a prosodic phenomenon). Because these differences involve both syntactic and temporally-bound properties, there may be an early process of encoding some temporally-bound components during the mapping between message and syntactic structure. The syntactic structure includes no indication of how the elements in the syntactic structure should be linearized, and cannot store prosodic information, and thus the sentence-level prosodic contour must be represented separately from the syntactic structure being generated.
4. **Syntactic structure mapped to segments of phonology:** Once the syntactic structure has been built, the next challenge is how that structure can be mapped to some kind of linear form in order to meet the constraints of the articulatory modality. The phonological word may correspond to a single syntactic unit (such as monomorphemic words in English), or it may correspond to a larger segment of the syntactic structure, even pieces that do not compose a single constituent. In English, contractions such as "I'll," "she's," "let's," or "dyawanna" (*do you want to*) involve a single phonological word that spans over a set of syntactic terminals that are not constituents. The ability to map phonology from larger segments of syntactic structure makes possible suppletion and allomorphy that are conditioned by the larger syntactic context. Thus, the output of this mechanism is a set of phonological units which may not transparently reflect syntactic structure. Various movement operations that occur in the interaction between syntax and phonology also happen during this stage [see Embick and Noyer (2001) for more details].
5. **Cognitive control:** The process of translating a hierarchical structure into a linear string is not a simple one. Many approaches in theoretical syntax assume that a syntax tree encodes no inherent order, only sisterhood and hierarchical relations between units. Rather than a 2-D tree, the representation is more like a spinning mobile. We suggest that cognitive control mechanisms act to facilitate the linearization of this structure. In cognitive science, "cognitive control" generally refers to a collection of processes that help people to complete goal-directed tasks by sustaining the representations required for the task at hand, while inhibiting unrelated or distracting ones. We suggest that in language production, cognitive control is used to sustain linguistic representations and decide between multiple alternatives for linearization. Because each terminal node in a tree may not correspond to its own phonological word, the speaker must hold the syntactic configuration in memory while also identifying the sets of syntactic terminals that would translate to each phonological word and deciding between multiple mapping alternatives. Though the syntactic configuration constrains which elements are put together, the mechanism responsible for mapping syntactic structure to phonological graphs is also sensitive to linear transition probabilities, so other potential mappings are made available which may not be correct given the syntactic structure. Cognitive control mechanisms provide the additional attentional and decision-making resources that the phonology-mapping mechanism needs to identify the correct set of phonological segments for the given syntactic structure while inhibiting others, helping to navigate a complicated translation space.
6. **Local phonology and phonological buffer:** The next data structure translation moves the proto-utterance closer to a linear string. After the phonological segments have been specified in relation to the syntactic structure, they must be syllabified, and other final re-ordering steps and phonological constraints can apply. This representation also acts as a buffer, holding the output string in memory and releasing phonemes for articulation at the correct time.
7. **Post-syntactic prosody:** In the mapping between the phonological graphs and the linear string, there must be an influence of phonological stress and prosodic weight in linearization operations. For example, the decision between a double object construction and a prepositional dative is determined in part by prosodic factors, namely the lexical stress properties of the indirect object and the verb (Anttila et al., 2010). Using additional evidence from Irish, Elfner (2011) similarly suggests that the rightward movement which appears in pronoun postposing must be prosodic in nature, rather than syntactic; syntactic movement tends to be leftward, and should not be motivated by the phonological content of the moved elements, so this would otherwise be highly irregular. By controlling when the phonological wordforms are released into the buffer, this linearization mechanism post-syntactically rearranges prosodic

phrases, and helps to prepare them to be computed into a string of phonemes.

8. **Articulation:** Finally, the linearized string of articulatory gestures is sent off to various articulatory motor mechanisms, in order to be produced.

Details aside, this brief summary of our forthcoming model is meant primarily to illustrate how cognitive and neural models of production can easily be constructed around non-lexicalist theories of the organization of linguistic knowledge. Although this preserves many of the insights of lexicalist production models, such as the idea that the syntactic processes generally precede phonological processes (Levelt and Indefrey, 2000; Ferreira and Slevc, 2007), in our non-lexicalist model the assumed stored representations are different, and the kinds of translations which those representations undergo must also be different. This non-lexicalist production model makes no distinction between "structural processes" and "lexical processes," because the syntactic units which combine in the syntax are governed by the same syntactic processes. As motivation for the Consensus Model of language production, Ferreira and Slevc (2007) emphasize a distinction between "content" and "function," in order to explain how language can be simultaneously systematic (linguistic expressions have consistent, identifiable meanings) and productive (linguistic expressions can be combined in infinite ways). A non-lexicalist model like ours can model both the systematicity and productivity of human language without such a distinction. Units of meaning are able to systematically map onto pieces of syntax, and pieces of syntax can systematically map onto units of form (conditioned on its syntactic context). Productivity is possible in this model because multiple units of meaning can map onto multiple pieces of syntax which can be combined in infinitely many ways, according to the syntax of the language.

We agree with production models which assume lexical items as treelets with much internal structure, such that stored linguistic knowledge can include large complexes of syntactic structure (Kempen and Huijbers, 1983; Vosse and Kempen, 2000; Ferreira, 2013; Matchin and Hickok, 2020). However, where these models typically assume as a fundamental property of the language system that each treelet has their own meaning and form, a non-lexicalist model like the one shown here allows more flexibility about how stored meaning, syntax, and form align, and does not require an additional process of lexicalization. In the non-lexicalist approach, there *can* be symmetrical "triadic" mappings, but this is not a necessary or central component of the language system. More broadly, non-lexicalist models that assume no "lexical" representations independent of meaning, syntax, and form, differ from neuroanatomical models that posit a distinct brain region or neural mechanism associated with "lexical nodes." For example, Wilson et al. (2018)'s model proposes that there is an area of the brain [the dorsal lip of the superior temporal sulcus (STS)] which is associated with lexical nodes, and that this region is spatially and functionally distinct from "higher level syntax.[7]" In our view, no such distinction is possible.

We have argued here for moving away from production models that center stored linguistic knowledge around lemma representations. Caramazza (1997) also famously argued against the lemma model, for slightly different reasons. Caramazza's point was that the experimental evidence which supports a two-stage model of lexical access—where syntactic and semantic information can be retrieved separately from the corresponding phonological form—does not entail that there must be a separate lemma representation as well. We are generally sympathetic to this conclusion. However we note that the alternative Caramazza proposed, the Independent Network Model, is different from standard non-lexicalist approaches in linguistics because it allows for direct mappings between meaning and form that bypass syntax [the Parallel Architecture model makes a similar assumption; (Jackendoff, 2002)]. Although our non-lexicalist model does not assume lemmas, it *does* assume that all phonological words and phrases which are produced have a syntactic representation. We think this is an important open question for future research.

3.2. Implications of the non-lexicalist approach for understanding aphasia

The non-lexicalist approach can generate different expectations about what deficit profiles will be observed in aphasia and other language disorders. In giving up the assumption that meaning, syntax, and form all share stored units of the same "size," this approach recognizes that the bulk of the work involved in language processing is in the translation between structured representations at each level, each with their own rules of well-formedness. Because the translation mechanisms are distinct, an impairment in one mechanism will not impact the others, creating the opportunity for deficits to be masked or distorted. For example, even though the mechanism which maps the message to syntactic structure is early in the production pipeline, disruption to this mechanism will not necessarily result in non-fluent speech or an absence of grammatical material, given that the subsequent processes of generating the phonological form are intact and will apply their own rules of well-formedness.

Based on this, we suggest that an impairment in the mechanism responsible for syntactic structure building would result in utterances that might sound fluent and seem to be conceptually well-formed, but involve errors in syntactic structure, as described for paragrammatism (Matchin et al., 2020). In this situation, all of the pre-syntactic operations are functioning well so the message itself may be well-formed, but its mapping to syntax exhibits some errors; the message may be mapped to the wrong pieces of syntax, there may be difficulties selecting all of the required pieces of syntax, or different parts of the message may be mapped to incompatible pieces of syntax. However, in a seemingly contradictory way, the utterance which is ultimately produced may appear to be well-formed, simply because the post-syntactic operations are functioning well. The subsequent mechanisms which map the syntactic structure to a phonological form may use transition probabilities and "default" forms to supply missing pieces that were not provided by the syntactic structure, satisfying the well-formedness rules of the phonology, making it

7 Wilson et al. (2018) observed that the dorsal lip of the STS responded to both backward speech and scrambled writing, and that the response was seemingly equivalent in both visual (written) and auditory (spoken) modalities. Based on this observation, they concluded that this modality-independent response in the absence of linguistic content or structure suggested the activation of lexical nodes. We favor other explanations; for example, this effect could be the product of modality-independent phonological processing, which is well-known to occur during reading as well as speech.

seem as if there are fewer errors in the syntactic structure than there actually were. Even if large pieces of the syntactic structure are missing or incorrect, the language system may be able to produce something that appears phonologically well-formed, even if it does not correspond to the message that the speaker intended. We assume that the relevant circuit for syntactic processing is localized to the posterior middle temporal gyrus and superior temporal sulcus, consistent with Matchin and Hickok (2020) and Matchin et al. (2020).

A useful metaphor for this is an assembly line in a factory that makes and decorates cake. The assembly line has three steps: making the batter and pouring it into molds (meaning mapped to syntactic structure), one that bakes and stacks the layers of cake (building the syntactic structure), and one that decorates the outside of the cake with fondant and frosting (phonological operations). If the machine that bakes and stacks the layers of cake is broken, it might under- or over-bake the layers, stack the layers incorrectly, or damage the layers along the way (creating an ungrammatical utterance). However, once the cake gets to the frosting machine, the frosting will make it look like a beautiful cake even if the structure of the cake is faulty (producing a phonologically coherent sentence, despite its structural flaws).

In this way, appearances can be deceiving. As long as a given string is phonologically well-formed, as external observers we may not necessarily know if it was also syntactically well-formed. By moving away from the "triad," just knowing that a phonological word was correctly produced may not be indicative that its meaning and syntax were also correctly generated, only that a form was produced. The only part we have direct access to is the utterance. For that reason, testing theories of aphasia may require more careful thought about what other processes may be at work beyond the one mechanism which is impaired, and how they might hide the real deficits.

Conversely, agrammatic aphasia (also Broca's aphasia, or non-fluent aphasia) is the type of aphasia that has often been described as a syntactic deficit, arising after lesions to the left IFG. It is characterized by "telegraphic speech" that seems to lack function words and inflectional morphology. Many of the observed deficits in non-fluent aphasia associated with inflectional morphology may not indicate a deficit in the representations of those morphemes, but instead that cognitive control is an unappreciated contributor in the linear placement and pronunciation of those morphemes. The impact of this kind of impairment may not be uniform cross-linguistically, given that languages with less flexible morpheme ordering may not involve such complex processes, as the number of plausible linearizations for those morphemes is reduced. Languages like Kalaallisut (West Greenlandic), a polysynthetic language, have a generally fixed morpheme order, with less variable forms; therefore, linearization processes for the morphemes within a single word should involve less cognitive control. It has been observed that speakers of Kalaallisut with non-fluent aphasia do not exhibit the usual pattern of deficits for functional morphology, and are able to produce the rich inflections of Kalaallisut words with a high degree of accuracy (Nedergaard et al., 2020). While morpheme order is generally fixed in Kalaallisut, word order is not; speakers of Kalaallisut with non-fluent aphasia do tend to produce fewer words in a single utterance, even while the words themselves are well-formed. This cognitive control mechanism, therefore, can contribute to varying degrees depending on the range of different linearization options available to a given structure.

Furthermore, it is often reported in the literature that non-fluent aphasia is associated with deficits in regular verb inflections, more so than irregular verb inflections, as an impairment in the grammar (Pinker and Ullman, 2002). However, a meta-analysis has shown that the pattern of deficits for regular and irregular verb inflections actually varies widely across language groups (Faroqi-Shah, 2007); German and Dutch speakers appear to exhibit disproportionate deficits for irregular inflections instead. As discussed by Krauska and Feldman (2022), the variability in the pattern of deficits cross-linguistically can be attributed to other factors such as verb frequency and form predictability. In the non-lexicalist approach, the relevant process involved in providing the inflected form of a verb is the mapping of syntactic objects to phonology, in a way that is probabilistic and context-sensitive. Given this, we are able to suggest that a speaker's success at this task can be conditioned on the predictability and frequency of the transformation. Consequently, the difference between German speakers and English speakers in inflection deficits may arise due to other differences in the past-tense inflection in those two languages, rather than representational differences.

Another commonly observed deficit in non-fluent aphasia is related to verbs (Thompson et al., 2012). This can also be understood as an issue of linearization, involving verbal argument structure and the linear ordering of the elements in the sentence, which can be specified for individual verbs, and exhibit some variability depending on the structure of the sentence. For example, in the sentence, "John gave some flowers to Susan," the elements can be arranged in a number of ways:

(5) a. John gave some flowers to Susan.
b. John gave Susan some flowers.
c. Susan was given some flowers by John.
d. Flowers were given to Susan by John.

Even if the decision between the different constructions can be motivated by different factors (information structure, discourse, etc.) these are all possible ways that the elements in a sentence might be ordered. The cognitive control required to produce one of these four sentences—while inhibiting the others—is not trivial.

4. Conclusion

At this point, one might be asking, what is a "word" then, if not a triad of meaning, syntax, and form? It is true that as language users, we seem to have intuitions about wordhood, about what constitutes a single word and what does not (even if those intuitions may vary). However, those intuitions are hard to formulate into a coherent hypothesis about linguistic units (Haspelmath, 2017). Wordhood should not be defined as a "unit of meaning," because things which are "intuitive words" may not be meaningful (as in the expletive *it* in the sentence *it is raining*), because a single unit of meaning may not correspond to an intuitive word (as is the case for idioms and some compounds), and because an intuitive word may not correspond to a single unit of meaning (a verb often includes tense morphology which encodes additional meanings, and the same holds for contractions[8] and morphologically complex intuitive words). We also cannot ground intuitive wordhood in being a "unit of syntax," because syntactic operations can apply to units smaller than intuitive words, as illustrated by the Inuktitut and Vietnamese examples. It also does not seem that we can ground intuitive wordhood in being a "unit of phonology," because there exist many phonological words (which define the domain of phonological operations) which are not intuitive words, such as "*dyawanna*" ("do you want to") in English. It could be that most of our intuitions about wordhood are in fact grounded not in natural spoken language, but in orthography, among literate communities whose writing system make use of white spaces as separators. For readers of such orthographies, "word" could serve as a useful term for the things between white spaces, which might well define processing units for the reading modality. However, many other writing systems have not made use of this convention, and it is notable that those speakers often have much less developed intuitions about wordhood (Hoosain, 1992). In summary, it is hard to see how speakers' intuitions about wordhood systematically correspond to any representational or processing unit of natural spoken language, although they could correspond to units of certain written languages.

To summarize, lexicalist approaches to language production struggle to account for a number of linguistic phenomena. We have argued here that in order to achieve broader coverage, models of language should not assume a split between morphology and syntax, or that there are "lexical items" which function as triads of meaning, syntax, and form. This knowledge should instead be represented as mappings from meaning to syntactic atoms, and mappings from fully abstract syntactic atoms to form. Non-lexicalist models of the kind outlined here align better with contemporary syntactic theory, providing a coherent production model without relying on lemmas or lemma-like representations. In doing so, such models are better able to capture cross-linguistic data and generate clearer predictions for linguistic behavior in those languages. Within such models, there is space for language-specific optimization processes based on the reliability of mappings between different representations, and the number of licit possibilities for that mapping, which may vary across individual words or phrases and between different languages. Finally, we have argued that non-lexicalist models can provide a new perspective on the processes and representations that may be impacted by aphasia and other language disorders, hopefully contributing to a better understanding of how language production mechanisms are implemented in the brain and the nature of language deficits after a brain injury.

8 It should be noted that contractions are a case where speakers seem to have less clear intuitions about wordhood (e.g., whether "we've" should be counted as one word or two).

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AK contributed to the conceptualization and wrote the first draft of the manuscript. EL was involved in conceptualization, supervision, and funding acquisition. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Correlated attributes: Toward a labeling algorithm of complementary categorial features

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Classical syntactic features are revisited from an algebraic perspective, recalling a traditional argument that the ±N vs. ±V distinction involves correlated, conceptually orthogonal, features, which can be represented in the algebraic format of ±1 vs. $\pm i$ complementary elements in a vectorial space. Coupled with natural assumptions about shared information (semiotic) systems, such a space, when presumed within a labeling algorithm, allows us to deduce fundamental properties of the syntax that do not follow from the presumed computation, like core selectional restrictions for lexical categories or their very presupposition in the context of a system of grammatical categories. This article suggests how that fundamental distinction can be coupled with neurophysiological realities, some of which (represented as mathematically real) can be pinpointed into punctual representations, while others (represented as mathematically complex) are, instead, fundamentally distributed. The postulated matrix mechanics amounts to a novel perspective on how to analyze syntactic neurophysiological signals.

KEYWORDS
categorial features, merge, punctual vs. distributed, matrices, real vs. complex entries

1. Introduction

Syntax has profited from the Computational Theory of Mind (CTM, Fodor, 1975), which sustains recursion—a hypothesis that Generative Grammar was central in establishing. In the current Minimalist Program (MP), the recursive operation *Merge* (M) is foundational, as is the presumption of a computational system of human language: C_{HL}. The force of this assumption has taken some to seek M in neurophysiology. Frederici (2017), for instance, asserts that "Merge has a well-defined localization in the human brain," in "the most ventral anterior portion of the BA 44"—within Broca's area, the premise being that "neural activation reflects the mental construction of hierarchical linguistic structures." Many are interested in grounding the categories M relates[1], correlating the presumed symbols to brain events. Friederici herself suggests that different neuronal networks, bound by fiber tracts, support the presumed syntactic processes, as well as a functional language network (FLN) at the molecular level, inferring information to flow "from the inferior frontal gyrus back to the posterior temporal cortex *via* the dorsal pathway" (p. 129).

Other researchers are more guarded. Emphasizing how theories of the brain, T_B, and theories of the mind, T_M, appear orthogonal to one another, Embick and Poeppel (2015) stress how "although cognitive theories and [neurobiology] theories are advancing in their own terms, there are few (if any) substantive linking hypotheses connecting these domains." Two reasons

1 This is regardless of whether one assumes a "meaningful" or a "fee" variant of M, which one of the reviewers asks about. As discussed below, the issue is presented from a different perspective in present terms, where to the extent that any M is meaningful, this is because of the free operation of the algebraic labeling system, with its own formal constraints.

underlie that *incommensurability*: (i) "computational/representational and [neurobiological] theories have... distinct ontologies" and also (ii) there appears to be a granularity mismatch at the level of analysis. T_M deals with formal devices and their interactions, while T_B deals with waves and how they overlap in time sequences, across brain regions. Correlation questions then arise: are T_M and T_B elementarily equivalent? Is one an extension of the other? Do they share a common model or at least a mapping? Poeppel and Embick (2005) plead that the computational/representational theories of language can be used to investigate its foundations. It is worth asking how such hopes can materialize, also for two reasons.

One reason has to do with what appears to gear neuroscience. It is useful to check, for example, its Wikipedia entry[2], where the discipline is described as "a multidisciplinary science" that is taken to range from biophysics to statistics, including medicine, chemistry, psychology, or computer science. Linguistics is only briefly mentioned *via* neurolinguistics, described as "the study of the neural mechanisms in the human brain that control the comprehension, production, and acquisition of language." The relevant entry for that subdiscipline[3], in turn, has relatively little bearing on the theoretical issues that concerned Embick and Poeppel (2015). While this is meant as a mere sociological indicator, it can be distressing, particularly when approaches that have emerged as self-perceived opponents of the CTM are seen as a priori more relevant, inasmuch as they deal with so-called neural networks, whose relative success mesmerize much of the general public[4].

The second reason for caution stems from the realities of MP as it stands, as reviewed in Lasnik and Uriagereka (2022). It is easy to show that the CTM is tangential to whether the phenomena we model should exhibit, for instance, selectional restrictions or separate into lexical and functional interactions. It seems at right angles with the computational aspects of the CTM, its finitistic nature, and its properties of systematicity, productivity, or transparency, whether computations are bottom-up or left-to-right, splitting into form and interpretation, or even when lexicalization happens. More generally, it is unclear whether relevant units—a syllable or a verb phrase—are categories, interactions, or whether it may all depend. It seems unlikely that future empirical research will demonstrate that vowels and consonants actually do *not* organize into syllables or that languages do *not* universally distinguish nouns and verbs. But "associationist" alternatives to the CTM are quick to presume that relevant conditions "emerge" from the communicative strictures taken to affect language, the idea being that hallmarks of the system are effective stabilities within an interconnected ensemble. While that may be hard to ascertain, there is nothing much that the CTM has to offer about substantive realities, or why the system is not carried on other modes of expression. It is all summarily blamed "on the interfaces," except those too tend to say little as to why that is, as opposed to some reasonable alternative.

The call for the present volume probes "Which brain regions support syntax, what are [its] temporal dynamics ...; and is [its] processing separable from lexical and semantic processing?" We ask because we do not know. We have a consensus that Broca's area is key, which we get glimmerings of in deficits like Broca's aphasia. We know this remarkable system manipulates and carries a particular kind of information forward in time—in Gallistel and King's (2010) memorable characterization of memory—but we lack an understanding, yet, as to what even a symbolic unit *is*, whether it is consonants/vowels or their interactions into syllables, nouns, verb phrases, and long-range correlations. In what follows, I delve into these matters from the perspective of correlated categorial features, as reviewed in section 3, after assessing the syntactic problem of types, tokens, and crucially (long-range) occurrences in section 2. The technical solution I have proposed elsewhere is discussed in section 4 and the proposal for a neurophysiological approach is introduced in section 5.

2. Types, tokens, and occurrences

The CTM generally presumes Marr's (1982) Tri-Level Hypothesis in treating vision as an information processing system—with three levels of analysis: (i) computational (what problems the system solves), (ii) algorithmic/representational (what representations it uses), and (iii) implementational (how it is physically realized). Pylyshyn (1984) interpreted these as intentional, symbolic, and biophysical. We do not have a good understanding yet of how even the more abstract intentional level connects to the symbolic one. The relationship (between expression and meaning) is philosophically taken to be a *representation* between a subject and a theory of a formal language, correlating a symbol and what it stands for. Arguing that there is no simple referent in the natural language examples this hypothesis presupposes, Chomsky (1993) has been consistently critical of our understanding of this particular relationship. Bringing this to formatives of grammar, elements manipulated in syntactic computations include sentences, phrases, words, all the way "down" to features. The question is what the putative *representational* relationship is between feature F, word W, phrase P, sentence S, etc., and whatever F, W, P, or S, ultimately signifies for the linguistic system.

In these terms, we tell ourselves that, for instance, the feature *voiced* in phonology (separating the first phoneme in *bit* vs. *pit*) *represents* something in neurophysiology (e.g., *voice onset time*, VOT, see Poeppel, 2003)[5]. It is, however, unclear whether the "representational" claim helps us understand what the phenomenon boils down to, let alone more abstract notions like phrases and the like. Are we to seek a literal representation for the projection of what syntacticians call (little) *v*, so that we can expect to (eventually find) *v*P within the FLN? This can get quite abstract when considering long-range correlations presumed for bound-variable bindings. To date, a fair amount is understood about the intentional/computational level and speculations exist about the "lower" symbolic (for Pylyshyn) or algorithmic (for Marr) level; some are even willing to consider a Tractable Cognition Thesis [van Rooij (2008), see Balari and Lorenzo (2012) for a minimalist view], taking human computational capacities to be constrained by computational tractability. All of that seems relevant to neurophysiology, even if one can independently measure brain activity with whatever technology or technique may become available.

2 https://en.wikipedia.org/wiki/Neuroscience

3 https://en.wikipedia.org/wiki/Neurolinguistics

4 See for instance https://openai.com/.

5 See Idsardi (2022) for mental maps regarding phonemes generally along these lines.

In between the computational and implementational levels, conditions on the algorithmic level, and in particular computational tractability, may actually vary depending on the biophysical support of the presumed algorithm, for example depending on how much parallel computation they allow [see Rieffel and Polak's (2011) introductory chapter on this, for a broader perspective]. The syntax is often likened to "Lego rules": smaller and smaller pieces combine to yield structures within some aggregative architecture (Baker, 2001). Cognition from this perspective translates into systematically manipulating symbols in combination with the internal states of some Turing machine, its details (whether carried by neurons or silicon chips) being irrelevant if computational inputs are arbitrarily represented. It is at that foundational assumption that alternative foundations bottom out - less "legos" than separable states in entangled networks. While classical computations build the system constructively from bits, from the parts to the whole (including the difficult emergence of long-range correlations), computations may also work *restrictively*, with long-range correlations in the nature of the ensemble itself; the issue then being under what circumstances these separate into classical units.

To be candid, no one could seriously affirm that the mind phenomenon, at least with regards to language as we experience it, is not classical in some fundamental sense, since obviously we remember words and they are different from one another (even if related in intricate ways). We know not just that the word *pet* is different from the word *charming*, but also from the word *bet*. At the same time, is the *feature* separating *bet* from *pet* (intuitively relating to VOT) exactly the same as the feature separating *bit* from *pit*? If this identity of features indeed obtains, how does the brain store feature types like F that get distributed over token uses as the need emerges—e.g., VOT for *bet*, *bit*, "the same" for each relevant word?

Color perception may be a relevant model (see Palmer, 1999). This starts with activating light-sensitive (retinal) cones, the types of which allow for various nuances (selectively deactivated in "color-blindness"). In this view, there would be some locus for VOT that gets invoked when pronouncing a voiced phoneme. But it could also be that, as they get more abstract, features are somehow distributed over a network of words like *pit* and *bit*, in which case we need to think about what it means to have information thus dispersed. The identity of token uses of a word like *bit* need not be the same as the identity implied by the VOT associated with given features. While folks seem aware of their knowledge of words—being able to comment on (never) having heard them—only language scientists care about feature uses, the ultimate repository of relevant features still being debated. In short, classical memory concerns seem rather more relevant to words than to their underlying features.

Only the most abstract features may enter into entangled ensembles of the sort relevant to long-range correlations. For instance, so-called φ-features surface *via* the phenomenon of agreement, across domains and under tight strictures (c-command or locality), none of which matters to VOT triggering. If a feature does not participate in long-range Agree specifications, why should one think of it in computational terms that presume such a correlation? In contrast, though, for features where said correlations are manifest, assuming the correlations in the ensemble does simplify our analysis.

Bear in mind how syntactic ontologies really go well beyond type and token distinctions, into *occurrences* in the general sense of Quine (1940):

(1) *Some politician seems to hate every reporter after meeting them.*

(2) a. $\exists x$ *politician*(x) [$\forall y$ *reporter*(x) [x *seems* [x *to hate* y [*after* x *meeting* y]]]]

b. $\forall y$ *reporter*(y) [$\exists x$ *politician*(x) [x *seems* [x *to hate* y [*after* x *meeting* y]]]]

Sentence (1) is structurally ambiguous, as in (2), with each representation of variables x, y as occurrences thereof, whose denotation happens to be distributed over the quantifier-variable dependency, thus simultaneously expressed over various configurations. This leads to many formal complications[6]. The problem boils down to what it means for the system to copy the relevant information and how that differs from bonafide repetitions of that information. Compare[7]:

(3) a. ***Some*** *seem* ~~***some***~~ *to hate problems.*

b. ***Some*** *seem as if* ***some*** *hate problems.*

In most minimalist proposals, (3a) involves two occurrences of (copied) *some*, while in (3b) *some* is fully repeated, not copied—each repetition bearing independent and autonomous reference. However, the English lexicon only has one lexical type *some*, "tapped" twice in (3b) but only once in (3a).

The theory also presumes that there is a full copy of *some* as in the strikeout representation in (3a), because of "reconstructed" examples as in (4), which presuppose anaphoric licensing:

(4) a. ***Some pictures of himself*** *seemed to Trump* ~~***some pictures of himself***~~ *to create problems.*

b. ***Some pictures*** ~~***of himself***~~ *seemed to Trump*$_{i}$ ~~***some pictures***~~ ***of himself***$_{i}$ *to create problems.*

The gist of Chomsky (1995) analysis is simple. Whereas the representation yielding the overt PF is of the sort in (4a), the one covertly leading to LF is as in (4b), the anaphor "reconstructed" (interpreted) in the structurally lower site, under the scope of the co-indexed antecedent. This, note, implies that copied tokens are interpreted *at one of their occurrences*. While a well-characterized phenomenon, this is a difficult outcome to obtain beyond stipulating the result itself, for unclear reasons.

The same issues arise for features, in languages exhibiting the relevant concord:

(5) *Terminad**as*** *l**as*** *tare**as**,* *parecí**an***
finished.FM.PL the.FM.PL work.FM.PL seemed.PL
l**as** cinco ya dad**as**,
the.FM.PL five already given.FM.PL

a. … *que puede que sea*<(***n***)> *hora*<(***s***)> *de ir a casa.*
which may.SG that be(PL) hour.FM(.PL) of to.go to home

b. … *que pued*<(***en***)> *ser hora*<(***s***)> *de ir a casa.*
which may(.PL) to.be hour.FM(.PL) of to.go to home

"With the work finished, it seemed to be past five, which is likely that it is time to be home already/to be time to go home already."

---

6 For example, as shown in the formulation in Collins and Stabler (2016), as also noted in Collins and Groat (2018).

7 I am attempting to show a minimal pair here, presuming raising in the first instance but not the second. Some minimalist theories have argued that non-standard movements also happen in the second instance, but I will set that aside now.

In Spanish (5), the copied or repeated item in this instance is the abstract bundle corresponding to plural and possibly also gender marking. Note that there are co-occurrence restrictions at stake: the sets of features within the sentential portions contained within the commas can be argued to be occurrences, while those across—although also identical in observed shape—are nonetheless repetitions with fully separate import, not mere copies that somehow spread within a domain.

The case of agreement repetition/copy is interesting on two counts. First, it is unclear what it would mean to copy anything in these agreement instances. The idea behind copies stems from generalizing the M operation—which assembles syntactic objects α, β (heads or their phrasal projections) into a set { α, β}—to conditions in which β is contained within α (i.e., $[_{\alpha} \ldots \beta \ldots _{\alpha}]$). Then the system creates a separate occurrence of β at the root of the phrasemaker: $[\beta\ [_{\alpha} \ldots \beta \ldots _{\alpha}]]$. But if this is how the syntax obtains copies through M, how could the copies presume, for instance, in the main sentence in (5) be obtained? Observe the relevant portion of the structure:

(6) $[_{T'}$ T$[_{VP}$*parecía**n***$[_{SC}$***las*** *cinco* $[_{PredP}$ *ya* *dad**as***$_{PredP}]_{SC}]_{VP}]_{T'}]$
seemed.PL the.FM.PL five already given.FM.PL

"It seemed to be past five." (Five seemed to have been struck.)

It is impossible to reproduce this sentence in English, where subjects must be preverbal. In Spanish, though, one can leave the subject behind[8], but the concord still shows up in the verb *parecían*, literally "(they) seemed", with a mark of plurality, in agreement with the subject in point. Now the key here is that, in that representation, the subject has not actually been copied (*via* "internal" M, IM) at the beginning of the sentence: it appears *in situ* instead. So the agreement occurrences that one observes in said verb must have gotten there some other way.

One may be tempted to open some semantic file to deal with such agreement occurrences, which after all show up in quantificational instances as in (3) and (4), where the presumed co-variations led Quine to his 1940 proposal about variable occurrences. Then again, there is not much of a reference at stake in the occurrences in (6): here they are purely formal, accessing indications of time that, thus, get spread over the sentence. While one may speak of reference to politicians and reporters, it is less obvious what that might mean for *five o'clock*, which in Spanish happens to be the feminine plural, arbitrarily so. Indeed, in an acceptable variant of (6) without concord, the morphological features that still show up (third person singular) do so "by default"—which absolutely lack referentiality. In sum, something allows these features to spread throughout syntactic domains, sometimes as occurrences, others being lexically accessed as separate token features, which happen to be identical (e.g., FM.PL) to other features independently occurring in the structure [as boldfaced in (5)]. The question is whether these instantiations of feature types are tokens or, instead, occurrences.

Here is the punchline then: while classical computational systems are generally quite good at building interactions of the token sort, by accessing types within some long-term repository (a lexicon) and treating them as building blocks, they are less apt to create these immaterial occurrences, only the collective of which end up amounting to a token, in some aggregative fashion. In contrast, computations building on correlations do just that, by their very design: the (relatively) easy part is to model the interaction in abstract space, while the hard job is actually to have any of that collapse into observables that behave classically enough to get pronounced, obtain concrete interpretations[9], and to crucially be stored in some reliable way that makes future access straightforward. Then again, the linguistic system seems to be telling us, also, that the task is performed so delicately that it can be mediated by long-range correlations allowing such nuanced expressions as those discussed in this section, which no classical computation has been able to state without resorting to arbitrary codings.

3. Features in a Functional Language Network

Supposing a neurophysiological FLN, what sort of information does it manipulate? The theory an FLN presumes computationally rests on underlying features. This was the case for Chomsky since his transformational 1955 manuscript. In the appendix to chapter 4 of the unpublished version[10], the reader is reminded that the "analysis into Nouns, Verbs, and Adjectives is a fundamental one… into four categories N, V, A, and X (everything *else*), with heavy overlaps." By 1981, Chomsky was taking the overlaps to be "based on two categories of traditional grammar: substantive … and predicate." Indeed, Varro had spoken of a similar intuition in *De Lingua Latina*[11], when reminding us how "… the Greeks have divided speech into four parts, one in which the words have cases, a second in which they have indications of time, a third in which they have neither, a fourth in which they have both."

That idea resurfaced in Chomsky (1974), where it was taken as a working hypothesis that:

> … the structures of formal grammar are generated independently and … associated with semantic interpretations by… semiotic theory… Under this hypothesis one would expect to find systematic relations between form and context [sic] … [T]he organism has the theory of formal grammar… as a basis for language learning that will allow certain grammars… [p. 21]

Since the manuscript was never edited for publishing, it is unclear whether Chomsky meant "form and *content*," but either way it is clear that he was arguing for the autonomy of syntax while exploring how it may relate to meaning, which relates to the Projection Problem[12]. In 1974, Chomsky was already pursuing a *restrictive* theory (for explanatory adequacy), hypothesizing a grammar to be "a system of constraints on derivations," so as "to restrict the class of possible

8 Although one could also say *las cinco parecían ya dadas*, literally "five seemed to have been struck".

9 Often of a referential sort, such that one could point at something or single it out in some model.

10 This was co-authored with Peter Elias and circulated in mimeographed version, chapter 5 of the 1975 published version, which unfortunately does not include the Appendix.

11 Vol 2: Book IX, XXIV-31, translated by Kent (1938).

12 As formulated in Peters (1972) and Baker (1979), this amounts to determining some mapping from primary linguistic data to an acquired grammar, under conditions presuming the poverty of the stimulus that underdetermines data for the acquisition task (see chapter 2 of Lasnik and Uriagereka, 2022).

systems" (p. 23, lecture 1). He had already signaled there (albeit as a "secondary consideration") the minimalist desideratum that "the restrictions that we impose on the theory [should] be in some poorly understood sense natural."

Chomsky's more technical discussion in 1974 is as follows:

> As far as the categorial component is concerned, it seems to me plausible to suggest that it is a kind of projection from basic lexical features through a certain system of schemata as roughly indicated in [7] and [8]:
>
> (7) [±N, ±V]: [+N, −V] = N[oun]; [+N, +V] = A[djective]; [−N, +V] = V[erb], [−N, −V] = everything else;
>
> (8) $X^n \rightarrow \ldots X^{n-1} \ldots$, where $x^i = [a = \pm N, b = \pm V]^i$ and $X^1 = X$. Let us assume that there are two basic lexical features N and V (±N, ±V). Where the language has rules that refer to the categories nouns and adjectives… they will be framed in terms of the feature +N and where there are rules that apply to the category nouns and adjectives, … in terms of the feature +V. [Chomsky, 1974: Lecture 3, p. 2]

This is Chomsky's way of addressing the "heavy overlaps" from Chomsky (1955)—the features representing relevant correlations. It is worth exploring those more thoroughly.

Note that the "else" category category from Chomsky (1955) remains in Chomsky (1974), over combinations of the [−N, −V] type. The fact that it is both features that entail the elsewhere case suggests they are correlated. More generally, in Lecture 3 of 1974, Chomsky spoke of "rules that refer to the categories nouns and adjectives [+N] … and … rules that apply to the category of verbs and adjectives… framed in terms of the feature +V." He also considered "lexical categories" as those with "feature complexes that give N, A, and V" (with *some* positive values in the pair), once again suggesting a correlation between the features themselves. By 1981, Chomsky was explicit about −N elements, which he took to assign Case (an idea that he was willing to extend to the functional category INFL) vs. +N elements that were taken to receive Case[13]. It is less obvious what feature ±V amounts to, beyond its being "predicative" (p. 46) for +V.

In 1981, Chomsky took "the Base component of the grammar" to consist of "the categorial component and… the lexicon, to which [he] assigned a central role in the syntax by virtue of the projection principle… [taking] the lexicon to be a set of lexical entries, each specified as to category and complement structure, with further idiosyncrasies" (p. 92). For Chomsky, the primary way to address the problem of projection from data to grammar is to take "the categorial component of the core grammar of a particular language… [to] be just a specification of parameters … with regard to ordering and internal structure of major categories… [T]he class of well-formed base structures for the language is determined by properties of lexical entries under the projection principle, and by… Case theory, perhaps also parametrized. Many potential grammars are excluded by these assumptions [within the] guiding principle of restrictiveness for linguistic theory." (p. 95)

In that context, Chomsky considered language-specific selectional restrictions, with auxiliary *have* rejecting [+N] complements, as compared to *be*, which takes [+V] complements (p. 55). The idea of "rejecting a class of complements" implies a disjunction[14], again a correlation between the relevant features. Chomsky discussed several other feature correlations; e.g., in terms of government and proper government (p. 50, 52, and 163; see fn. 16). On page 252, he considered the possibility that only "categories with the features [+N] or [+V]" are proper governors—this being closer to the notion of "lexical category" in lecture 3 of 1974[15], emphasizing attribute correlation within the features.

There are further passages in 1981 where Chomsky concentrates on feature attributes, neutralizing corresponding values (p. 52, pp. 117–118). One such is deployed for syntactic passives (treated as "neutralized verb-adjectives with the [sole] feature [+V]"). One must then surmise either a free-standing N attribute (instead of a pair (attribute, value), as presumed for any full feature) or else a ±N feature, with dual value. According to Chomsky, this is because "syntactic passive participles are sometimes treated as adjectival and sometimes as verbal"—again suggesting a correlation between feature values, which can thus be targeted in unison. On pages 127 and 142, fn. 49, Chomsky considered parameterizing such nuances, to distinguish English from Hebrew passives.

In 1974, lecture 3, page 3, Chomsky asserted that basic phrase-markers are "projected from the lexical categories uniformally," for "in a fundamental way the expansion of major categories like NP, VP, AP is independent of categorial choice of the head … [as] instantiations of the same general schemata." This is the origin of X'-theory, later to morph into the minimalist Bare Phrase Structure in chapter 3 of Chomsky 1995—instantiating M and presuming not just learnability considerations, but also economy/symmetry criteria. In that lecture, Chomsky seemed interested already in "subsidiary features" relating to "higher order endocentric categories." At that time, only INFL and COMP had been explored, and Chomsly in 1981 took the "S-system [not to be] a projection of V but rather of INFL," this category containing "the element AGR … when … [+Tense], where AGR… [stems from] a feature complex including [+N, −V] (p. 164)." The categorial system is, thus, not restricted to the lexical categories, but it extends to functional categories. Similar considerations apply to small clauses on page 169, as projections of an [+N, +V] element. Other authors within that theoretical framework raised similar questions about COMP (treated as adpositional in Kayne, 1994) or DET, once it became isolated as its own category (as relationally analyzed in Szabolcsi, 1983).

It is also interesting that A-chains were characterized in Chomsky 1981 (to distinguish them from A'-chains of Wh-movement) and restricted to [+N, −V] projections (see, e.g., p. 224, fn. 23). This raises the question of why A-chains should be thus restricted or why the Case/Agr system should target nominal projections only. If it were to target the +N elements it should extend to adjectives, and if −V elements, also to adpositions. But neither is the case, only the combination [+N, −V] is targeted for the transformational process in point, again emphasizing a correlation among those categorial features.

The foundational matters we have been sketching have not disappeared. Thus, languages:

13 Obviously noun projections, but also adjectival ones in relevant languages.

14 Here, of implicitly *permitting* [−N, +V] and [−N, −V] complements, which cannot be stated as a generalization over V.

15 Proper government was seen as a form of restricting long-range correlations involving traces (Lasnik and Saito, 1992).

(9) a. … distinguish lexical and functional categories, the latter being (relatively) structurally higher.
b. … separate the major syntax-articulating categories of nouns and verbs (even abstract ones).
c. … exhibit abstract features from nouns/verbs, arguably playing syntactic roles elsewhere.
d. … display sub-categorization and selection restrictions that are specific to a particular language.

In addition, after decades of studying how to constrain grammar, we continue to wonder:

(10) a. Why there are so many grammatical sub-theories about (extended) noun projections.
b. Why the grammar exhibits A vs. A' movement—and how it can be characterized.
c. Why A is movement restricted to (extended) NP projections.
d. Why A-chains "collapse" into a single occurrence (of many derivationally generated).
e. Why all long-range correlations are not clearly reducible to local correlations.

The list is neither meant as exhaustive nor is it clear that any available theoretical framework provides simple (let alone unified) answers to such questions.

In order to continue with a (biolinguistic) research program that should be able to directly address—or at least be guarded about—these foundational matters, it is instructive to explore ways in which to continue to formulate and constrain our theories, based on traditional considerations of feasibility. The following proposal is made in that spirit, noting how Smolensky and Legendre (2005) could be interpreted as a step in this general direction. While that work comes from a connectionist tradition that opposes the CTM (see Joe Pater's blog entries: https://blogs.umass.edu/brain-wars/the-debates/smolensky-vs-fodor-and-pylyshkyn/), it is not difficult to show how many of the basic presuppositions in this Integrated connectionist/symbolic (ICS) cognitive architecture can be achieved by one possible interpretation of Chomsky's 1974/1981 system of categorial features.

Without going into the ICS model, I will say this approach presumes two levels of description for cognition (as compared to the Marr/Pylyshyn classical approach). As Smolenksy (2006) puts it:

> Parallel distributed processing (PDP) characterizes mental processing; this PDP system has special organization in virtue of which it can be characterized at the macrolevel as a kind of symbolic computational system. The symbolic system inherits certain properties from its PDP substrate; the symbolic functions computed constitute optimization of a well-formedness measure called Harmony. The most important outgrowth of the ICS research program is optimality theory… Linguistically, Harmony maximization corresponds to minimization of markedness or structural ill-formedness. Cognitive explanation in ICS requires the collaboration of symbolic and connectionist principles.

The development of this architecture rests on the compositional embedding of symbolic structures in a vector space, *via* tensor product operations. While the approach has been applied to linguistic and psycholinguistic problems not reviewed here—let alone its ramifications into so-called deep learning—I acknowledge this connection while showing how one can get there from symbolic presuppositions.

4. A fundamental assumption and some consequences

Chomsky 1974 worked from the traditional idea that N and V dimensions are conceptually orthogonal—as different as can be, being comparable to whatever distinguishes consonants and vowels. When facing such differences in a substantive way, one pulls from binary cognitive dualities to maximize interpretive differences. It is interesting how those can be addressed when dealing with matrices presenting specific eigenvalues that correspond to subspaces—as labels for measurement outcomes. While such labels can be used to represent any given property (like energy in a corresponding eigenspace), this assignment is not crucial, any distinct set of eigenvalues sufficing (see Rieffel and Polak, 2011, p. 54). Taking that idea as formal inspiration, Martin et al. (2019) express the implicit "conceptual orthogonality" (between the N and V dimensions) through mathematical orthogonality[16]:

(11) *Fundamental Assumption*
The V dimension is a transformation over an orthogonal N dimension.

Instantiating (11) in the complex plane, we can then conclude:

(12) *Fundamental Corollary*
The N dimension has unit value 1; the V dimension, unit value i; $[\pm N, \pm V] = [\pm 1, \pm i]$.

The Fundamental Corollary thus allows for algebraic operation with these features, as we see momentarily. In the Appendix to Chapter 4, Chomsky in 1955 attempted to derive the four major categories his formal features covered on information theoretic grounds, suggesting that this view of the relevant features was distributional. Here too, so far, all we are presuming is that the N and V features are formally as distinct as possible—in other words, nothing much about their "meaning."

Chomsky (1981) did not seem to care about the order of the features he discussed. Although he normally listed them as the customary [±N, ±V], on page 48 [example (1)], he offers [V, ±N] as a possibility, which again surfaces on page 142, fn. 49, where he discusses [+V, −N] combinations. There is nothing wrong with this if the features are meant as substantive—the equivalent of advertising an item as "cheap, valuable" or "valuable, cheap." Then again, if the features are meant to be correlated, the order could matter, just as it is not the same to put a golf ball on a tee to then hit it than to hit a tee to then put a ball on it… The complex expression $(\pm 1, \pm i)$ expresses a different scalar from $(\pm i, \pm 1)$, which can also be said about related vectors. This is relevant in that, as noted, in 1981, Chomsky

16 Both reviewers ask for a comparison of the theory I am assuming with Adger (2013) and Panagiotidis (2014). Adger's monograph is a paradigmatic example of the opposite of what the present theory attempts: a syntax *of form*, not substance. Panagiotidis's is tangential, in that it questions the classical distinction the Chomskyan divide presumes; if the system in point is taken to follow from algebraic considerations, the putative correctness of that challenge would disprove the theory.

wanted AGR in INFL (one of several subsidiary categories) to be [+N, –V], small clauses corresponding to [+N, +V] projections. If an order does matter, these decisions can be immediately separated by describing them as [–V, +N] and [+V, +N], respectively—similar possibilities obtaining for a relational DET with verbal characteristics [+V, –N] or an adpositional COMP assumed as [–V, –N].

It is hard to see how to operate with lists of substantive features (like "cheap" or "valuable"), but quite easy to imagine how to do so with formally orthogonal features like [±1, ±*i*] or [±*i*, ±1], since the following equivalences hold when presuming an entry-wise—also known as Hadamard—multiplication (remembering that $i = \sqrt{-1}$, so $(\pm i)^2 = -1$ and $i\,(-i) = -i\,i = 1)$[17]:

(13) $[\pm 1, \pm i]\ [\pm i, \pm i] = [\pm i, \pm 1]$

Note, in turn, that [±*i*, ±*i*] emerges from [±1, ±*i*] [±*i*, ±1] and [±*i*, ±1] [±1, ±*i*] products, while self-products (squares) of these very elements are as follows, with [1, 1] never emerging as a product:

(14) a. $[\pm 1, \pm i]^2 = [1, -1]$; b. $[\pm i, \pm 1]^2 = [-1, 1]$;
c: $[\pm i, \pm i]^2 = [-1, -1]$

That [1, 1] category, however, does arise in many combinations. For instance:

(15) a. $[1, i]\ [1, -i] = [1, 1]$; $[1, -i]\ [1, i] = [1, 1]$;
$[-1, i]\ [-1, -i] = [1, 1]$; $[-1, -i]\ [-1, i] = [1, 1]$.
b. $[i, 1]\ [-i, 1] = [1, 1]$; $[-i, 1]\ [i, 1] = [1, 1]$;
$[i, -1]\ [-i, -1] = [1, 1]$; $[-i, -1]\ [i, -1] = [1, 1]$.

An entry-wise product by [1, 1], in turn, leaves any results unchanged, signaling an identity element:

(16) a. $[\pm 1, \pm i]\ [1, 1] = [\pm 1, \pm i]$; b. $[\pm i, \pm 1]\ [1, 1] = [\pm i, \pm 1]$.

This, together with a simple examination of any other comparable products, easily shows the emergence of a group for Hadamard multiplication from these interactions, of the following general shape:

(17) a. $[\pm 1, \pm i]$; b. $[\pm i, \pm 1]$; c. $[\pm 1, \pm 1]$; $[\pm i, \pm i]$.

While elements as in (17a) correspond to the Chomsky objects (per the Fundamental Assumption and its corollary), and those in (17b) may model functional categories associated with N, V, A, and elsewhere (e.g., P) projections, we need to consider what the other elements in the group correspond to.

Martin et al. (2019) model labeling in M (bare phrase) projections in such terms, for which they first consider a comprehensive characterization of M. The relation is often assumed to be asymmetrical, between a head (selected from the lexicon) and a phrasal projection (assembled in a syntactic derivation). That said, such an asymmetry is impossible when a derivational space is initiated, and we only have two *heads* from the lexicon. To keep M unified, though, one can presume it is *anti*-symmetrical, allowing reflexivity and otherwise forcing asymmetry in its terms. If M is to be thus interpreted, such a base condition—presuming reflexivity or asymmetry pertain to "level of projection" (whether the category projects)—entails that labeling in self-M (of the Chomsky objects) is equivalent to the squaring operations in (14a). This results in a trivial phrase, but a phrase nonetheless[18].

However, note that all the powers in (14a) result in the very same [1, −1] category, which seems senseless for a semiotic system. We may thus assume the following, for now as an axiom:

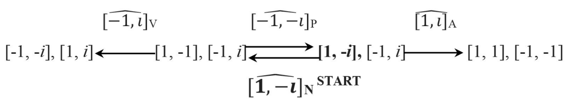
(18) *Anchoring Axiom:* Only N categories $[1, -i]_N$ self-M (with labeling $[1, -i]^2 = [1, -1]$).

There are some other reasonable assumptions one could make about the emerging algebraic system if it is to describe a semiotic/information algorithmic, recursive system; for example:

(19) a. All four category types within the group are deployed.
b. A given category must be included regardless of whether it falls into an equivalence class.
c. Categorial operators $\hat{O}$ maximize value diversity.

Maximizing said conditions, a labeling algorithm emerges. The system starts self-multiplying [1, –*i*] Chomsky's noun signaled by subscript N. The square of that category (where it is taken to act as an operator, represented with a hat "^", on itself) results in the N projection [1, −1]. The rest proceeds in like fashion, with the other categorial operators (the other three Chomsky categories). There are always "twin" results, an equivalent class in that the product of their values is the same −1 for the noun projections, *i* for the verb projections, –*i* for the adposition (elsewhere) projections, and 1 for the adjective projections. This equivalence leads to a refinement I return to momentarily. The graph in (18) carries a labeling algorithm with a START state and two possible END states, as well as presumed internal recursion. Although I will not prove this here, of all the possible multiplications the ensuing group allows, only those in the Jarret graph and those in a graph involving the mirror image of these categories (associated with functional categories, see fn. 25) satisfy the restrictive desiderata in (20).

(20) *Original Jarret Graph*[19]:



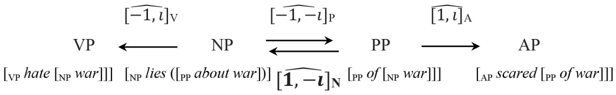
17 To execute these multiplications, readers need only multiply the corresponding entries between themselves. The vector schemata with multiple values represent separate vector types, one per value. The reason the 16 possible outcomes reduce to only four after the multiplication is because many of these multiplications are equivalent.

18 Building on an insight in Guimarães (2000), we take the problematic merger of *sail boats* to result into something like *sail boats-boats*, with two occurrences *boats-boats* that linearize as the token *boats* (the occurrences then collapsing).

19 This graph is so-called because it was suggested by quantum information theorist Michael Jarret. It takes a first step of self-M (matrix power) restricted by the Anchoring Axiom, yielding NPs, while restricting the identity element to adjectival projections resulting from an adjective taking a PP complement; in turn, the system presumes the two Chomsky objects involving identical values correspond to VP projections, while the two Chomsky matrices involving alternating values correspond to PP projections, in both instances by taking NP complements.

It is also not hard to associate the Jarret graph with elementary "subcategorization restrictions"[20]:

(21)



Importantly, these restrictions are not imposed here because of external (interface) conditions: they follow, instead, from the system's algebra, under the circumstances we have been examining. They would be different, for instance, if we were to change the Anchoring Axiom in (17), or we did not impose the information/semiotic conditions in (18). The take-home message: projections ("vertical") and selection ("horizontal") restrictions, which the Projection Problem encourages us to seek, follow from the "restrictivist" (labeling) theory, regardless of considerations of language use.

I mentioned a way to improve on the system: while the internal multiplication of the entries is of no obvious algebraic significance, it would be if, instead of just listing the features, we were to place them as diagonals in 2×2 square matrices (those being the simplest possible such matrices)[21]:

(22) a. NP: $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}_{-1}$; b. VP: $\begin{bmatrix} -1 & 0 \\ 0 & -i \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}_{i}$;

c. PP: $\begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix}, \begin{bmatrix} -1 & 0 \\ 0 & i \end{bmatrix}_{-i}$; d. AP: $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}_{1}$.

Now the subindices associated with the "twin" matrices are a well-known independent scalar: the matrix *determinant*, in this instance the product of the elements in the diagonal (the matrix *eigenvalues*)[22]. The twin matrices are, then, equivalent in that they have the very same eigenvalues, whose products result in the syntactic labeling without reference to the system's interfaces[23]. It is easy to show how the objects in (20) constitute an Abelian (commutative) group for matrix multiplication, directly satisfying the desiderata in (18) for a recursive semiotic/information algorithm, again with a START state at the object $\begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix}$[24]. I will not show this here, but once this matrix format is assumed, it can also be shown that the Anchoring Axiom becomes a theorem. This is because any anchoring of the system (*via* self-M, with labeling from a matrix square) in any other Chomsky matrix does not result in a semiotic/system satisfying the desiderata in (18)—so the Jarret graph is improved *via* 2×2 matrices[25].

Orús et al. (2017) show how a direct extension of the Abelian group in (20) also covers all other standard Pauli matrices (X and Y). It is also easy to prove how the Pauli group can be expressed by way of the Chomsky matrices, none of which is crucial now. It is noteworthy that the ensuring system can express relevant correlations in superposed conditions that I will not review now, but which have a direct bearing on the questions in (10), rationally modeling chain labeling as in (10d). I will set this central motivation aside now though, to focus on neurophysiological matters instead.

Important for our purposes is to gain some insight into what the Fundamental Corollary in (12) amounts to while equating N to 1 and V to i. If meant seriously, this will have an immediate consequence for Euler's identity relating i to -1, *via* the base e of the natural logarithms:

(23) a. *Euler's Identity:* $e^{i\pi} = -1$ b. *Linguistic version:* $\boldsymbol{e^{V\pi} + N = 0}$

While that may seem arcane, bear in mind the trigonometric expression in (22), also extended:

(24) $e^{ix} = cos\, x + i\, sin\, x$; for $x = \pi$, $e^{i\pi} = cos\, \pi + i\, sin\, \pi$;
$\boldsymbol{cos\, \pi + V\, sin\, \pi = -N}$

Euler's formula establishes a basic relation between complex exponential functions and trigonometric functions[26]. In the context of signal analysis, it is well-known from the Fourier series that any signal can be approximated to sums of sinusoidal functions, whose expression can be reduced to sines and cosines (Fourier analysis). Euler's formula allows us to express this algebraically. Thus, the Fourier Transform can be expressed indistinctly in terms of sines and cosines or in the boldfaced form in (25), the latter with implications now in that it gives a geometrical meaning to the fundamental assumption that the V dimension is a transformation over an orthogonal N dimension[27].

(25) *Feature Fourier Transform (FFT)*
$F(w) = \int f(x)[\cos(wx) - i\ \sin(wx)]\, dx = \int e^{iwx}\, dx$

Unpacking (25): the relation between the V and N dimensions can be seen as a Fourier transform *F(w)* between two correlated variables,

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20 $\hat{V}$, $\hat{P}$ operators take projections hypothetically associated NP, while $\hat{N}$, $\hat{A}$ operators take those hypothetically associated to PP. Empirically this is true (for nouns, adjectives, and adpositions) or statistically dominant (for verbs, in the more prevalent transitive condition—although that system extends to bi-clausality, di-transitivity, and their interrelations, which I cannot go into in the present context, where we have not thoroughly discussed corresponding functional categories).

21 Readers may check https://en.wikipedia.org/wiki/Linear_algebra or any introduction to linear algebra, as well as the helpful tutorials *Essence of Linear Algebra:* https://www.youtube.com/watch?v=fNk_zzaMoSs.

22 The Chomsky matrices stand in an eight-matrix Abelian group for matrix multiplication, where each has a *negative*, a *conjugate*, and a *negative conjugate* within other Chomsky matrices, as well as projections, each of which is its own conjugate. Those elements can be arranged into the Jarret graph, with which it is easy to define a simple Hilbert space.

23 So, the labeling algorithm is based on said determinants, more so than the matrices they are the eigenvalue products of. This, thus, is a direct way in which the present theory (postulating matrix determinants as formal labels) is the opposite of what Adger (2013) (or any theory presuming feature substance as foundational) presumes about syntactic labels.

24 This first Chomsky matrix, or *C1*, is categorially ambiguous between a noun and one of the "twin" PP projections. As a noun it can act as a categorial operator on itself, yielding self-M.

25 One can also state an "anti-Jarret" graph starting in the "flipped" version of *C1* that also satisfies (20), so deriving (18) as a theorem requires a stochastic decision: the grammar could have also been represented in a different vectorial basis. This is expected of systems expressed within vector spaces.

26 For a tutorial on the significance of Euler's formula, see https://www.youtube.com/watch?v=mvmuCPvRoWQ.

27 Calling these dimensions V and N, i and 1, or anything else is less important than recognizing the orthogonality. This is to say that Euler's formula could equally apply to, for instance, the relation between a vowel and a consonant space.

w and *x*, such that *w* corresponds to some wave expression and *x* to some measurable—those variables then being *complementary*. Given the logic of this FFT, the more accurate representation we obtain of *x*, the less we can ascertain the details of *w*, and *vice-versa*[28].

That formal complementarity can surface in a variety of linguistic contexts, just as it does in real-life situations (from acoustics to quantum mechanics). Lasnik and Uriagereka (2022), chapters 4 and 5, show how linguistic categories/interactions come in two guises: they may be *punctual* within the computation of a representation or, rather, *distributed*. In the realm of phonology, this is seen when comparing vowels (or continuant phonemes) to consonants (particularly stops). The phenomenon of alliteration banks on the repetition of the punctual stuff, while rhyme, instead, repeats the distributed information; a rhyme is distributed also in that, unlike alliteration, it can run across sentences. In terms of an equation as in (25), all we have to do is plug in the "consonant qualities" into N and the vowel "qualities" into V, and we have the presumed complementarity. We could think of it as a way to regulate articulators so that the more punctual they are, the less distributed, and *vice-versa*—but the complementarity remains as two aspects of the same FFT. The question is how to generalize that.

I lack the space here to go into various syntactic domains in which we arguably also obtain the complementarity the formal system allows, so I will discuss just one:

(26) a. *Verbs constitute examples, in this sentence.*
b. [$_{TP}$ Verbs [$_{VP}$ [$_{V'}$ constitute examples] in-this-sentence]]]
c. ∃*e* {Cause (*e*, *Verbs*) ∃*e*' [Theme (*e*, *e*') & Present-*constitute* (*e*') & Theme (*e*', *examples*) & *in-this-sentence*(*e*')]}

The issue is not lexical access to the encyclopedic knowledge coded in the items *verbs* or *constitute*, associated with the pronunciations /vərbz/ and /'känstə,t(y)o͞ot/. The point is that the interpretation of *verbs* as in (26)—more accurately, *verb*, without the plural marker—is essentially indexical with regards to the meaning of that root, whatever it happens to be (in this instance an abstract entity, but it could be the concrete *this verb*, a more concrete entity associated to a verb name, or an actual pointing by the speaker). For the purposes of that logical form, *verbs* are a constant that can be replaced by any other[29]. This is not the case for *constitute*, which goes together with sub-event and quantificational paraphernalia as in (26c) that can be changed (if the verb is intransitive, ditransitive, introducing a clause, etc.) and be further modified by aspect nuances, modals, perspective shifts, and more. Again, it does not matter that the encyclopedic information of this particular transitive verb is *constitute* (as opposed to *establish*, *comprise*, *represent*...), but the verb must have the particular thematic structure in (26c), which could be further enriched into structural nuances too numerous to go into.

Just as we saw for the consonants and vowels, the formula in (25) provides us with features in the relevant categories whose effect is to secure the verb gets distributed over an expression like (26), unlike the argument nouns. Of course, this will necessarily have to be more abstract than in the phonemic case, but it is mathematically comparable. We could thus conceptualize verbs as modeling classes of eventualities obtaining of given kinds with some probability[30], with the verb itself being a superposition of said probabilities. If so, the verb amounts to a probability ensemble (a wave of some sort), which can obtain a given realization through its subject in whatever context happens to be relevant. Usually, we presume phrasal axioms mapping syntactic objects to semantic representations. This is all fine, but also fairly arbitrary. The present system suggests that there are key features within the relevant categories that limit those mappings, so that, for instance, a noun phrase cannot be taken as the main event—unless, of course, there is a circumstance (e.g., an identification) in which this is actually plausible, relying on the fact that the relevant features are still complementary[31].

The linguistic version of Euler's identity tells us why, if the verbal label is the imaginary *i*, then the corresponding nominal label has to be the real -1[32], or in matrix terms why the verbal matrix is the negative of the nominal one. Once that is, the verbal matrix has the elsewhere one as its conjugate, just as the nominal matrix has the adjectival as its conjugate (and those conjugates are negatives of one another). In terms of projections, moreover, any matrix in the Chomsky/Pauli group associated with determinant *i* will be a verbal extension in the functional domain, the same generalization holding for any other matrices within the group associated with -1 for nominal extensions, 1 for adjectival ones, and –*i* for the elsewhere case[33], thus

28 This fact about the Fourier transform (https://www.youtube.com/watch?v=MBnnXbOM5S4) underlies Heisenberg's Uncertainty Principle—the correlation underlying the basis for quantum entanglement.

29 This is said largely for concreteness, not to go into the semantics of kinds. Obviously, individual variables too can discharge relevant thematic roles and be bound by their own quantifiers, leading to various occurrences as in (2) above.

30 For any conceptualized kind *k* that a speaker can conceive of, we could, in fact, consider what the relative probability is for *k* to be [e.g., for (26)] *constituted* (of such-and-such)—and similarly for other eventualities.

31 Mutatis mutandis, nothing prevents certain consonants from appearing as syllabic nuclei; it is a matter of perspective, which the correlation of features allows. This is because, in effect, we are presuming a (wave, particle) duality. This bears on an issue one of the reviewer's raises, regarding categorial gradience. As it turns out, in principle *any gradiance* could be expressed in terms of the correlated variables, so long as they are correlated. But the topic is too broad to explore here.

32 1 goes to the other side of the equation as -1, but the basis of the system could change, and so long as the four categories preserve their algebraic interrelations, nothing would (see footnote 26). Note also that aside from $e^{i\pi} = -1\ (= e^{i3\pi} = e^{in\pi}$, where *n* is odd), we also have $e^{-i2\pi} = 1\ (= e^{-i4\pi} = e^{-in\pi}$, where *n* is even), which makes sense if we think of this formula as corresponding to a unit circle, completed (and thus repeated) every two or any even number of π occurrences, and half completed at π, 3π, and so on, in the odd sequence. Linguistically, in that unit circle, $e^{V\pi} = -\text{N}$, $e^{-V2\pi} = \text{N}$, which amounts to saying that the ideal nominal representation is the conjugate of the ideal verbal representation, while the ideal adjectival representation is the conjugate of the ideal elsewhere (adpositional) representation, and that all four lexical categories correlate in the relevant underlying group. Moreover, "going in circles" amounts to representing the periodicity of some (aggregation of) sinusoidal waves, which may lead to characteristic complexity for each complex subcase within this general format.

33 Bear in mind that the determinant is the label for the "twin" projections, which are categorial arguments of the project*ing* categories, the operators (e.g., the Chomsky matrices). The operators do not have a meaningful twin and, if they have a label at all, this is intrinsic to the assumptions about the Euler identity, for instance stipulating that, say, V will be *i* by a choice of basis for the system. That is, in effect, the (unavoidable) anchoring step, that can also be stated from the point of view of N or, more generally, as the linguistic version of the equality: $e^{i\pi} + 1 = 0$.

covering a wider grammatical space without going outside the overall algebraic system, in principle allowing us to extend the Jarret graph to grammatical categories.

Several other such examples of the same sorts of correlations can be provided, for instance, Vendler's (1957) classification of verbal aspect, as refined in Rothstein (2016) to separate achievements and accomplishments that involve a punctual endpoint (the *telos*), unlike states or activities that are open-ended. Transformational representations in syntax, too, have to be distributed through the reach of their scope, which is at the core of the problem of distributed occurrences that were discussed above. Once again, the suggestion is that the labeling situation arising in transformational instances involving voice (among several others: questions, relativization, ellipses, and more) is in some fundamental sense akin to the distributed interpretation of a verbal expression as in (26c), per the FFT in (25).

5. What does a Feature Fourier Transform have to do with Neurophysiology?

One could treat each such instance in a piecemeal fashion, with different substantive assumptions and separate mappings to relevant representations. But the more daring consideration is that for some features (establishing basic scaffoldings) there is a deeper correlation that Chomsky hinted at in 1981. This labeling matter can be resolved internally to feature systems without altering what syntacticians, phonologists, or semanticists, do with their representation thereafter. The proposal presupposes all of that, suggesting that the way to address the odd behavior of occurrences—together with some systemic symmetries, like the sub-categorization generalizations the Jarret graph presumes—is by assuming a correlation between relevant scaffolding features as strong as in (25): a complementarity.

If nothing else, the claim is testable, indeed beyond grammatical considerations, which moves us into neurophysiology. The intuition is that, just as we encounter syllables articulated around vowels and bounded by consonants or aspectualities for telic expressions bounded by the end point of the event, we also confront sentences articulated around verbs and bounded by entities normally expressed through nouns. Moreover, in syntax we can turn categories into interactions by way of transformational procedures, in which case we invoke long-range correlations that typically make our representations grow in size, getting us into distributed instantiations of tokens into variable occurrences. In all these instances, the Fourier transform expects complementary variables w and x correlating in corresponding labels; we have sketched this for behavioral systemic outputs in phonology, syntax, or semantics, but in principle, one should see whether any such correlations obtain *for brain signals themselves*, at whatever level we manage to read. There may not, or we may not be able to unearth anything from the noise, but this should be the first thing to attempt, from two opposing foundational approaches.

From a conservative perspective, consistent with various theories, we expect "punctual" brain events to correlate with more definite indicators, spatially or temporally; in contrast, the "distributed" situations should be more dispersed and just harder to isolate. If any of this is on track, one should also see some putative correlation between those two types of observations. But a more radical approach is also mathematically possible; we may be able to pinpoint *only the "punctual" indicators*. This would be if, in fact, the brain wetware is, in any serious sense, obeying quantum mechanical conditions, where only certain outcomes correspond to measurable observables. I raise this point only to bear in mind a spectrum of possibilities, even if that option may raise more questions than it addresses.

More mundanely, we already distinguish (distributed) phenomena like *muscle tetanization* vs. ballistic gestures, which would seem relevant to phonological distinctions, among others involving muscle (groups) in animal activities. This is less obvious for the more abstract notions that pertain to syntax or semantics, but there too one may consider *active maintenance* of perceived categories vis-a-vis more punctual perception modes, presupposing, for instance, neural responses from visuospatial working memory (of some entity in space), which conjunctively track the entity's features and spatial coordinates. Each such conjunction requires a sustained neural response. While tetanization does seem relevant in sustaining tense (stressed) vowels, for instance as compared to ballistic phonemic gestures, a more nuanced matter is whether active maintenance is relevant in keeping a verb active as in (26c), distributed agreement occurrences of the sort in the Spanish (5), or a displaced noun phrase with the range of occurrences presupposed in (4). Moreover, one ought to worry about whether tetanization and active maintenance correlate, as implied if these phenomena instantiate the same underlying FFT[34].

The presumed lexicon that syntax operates on in this general approach is of the sort in Smolensky and Legendre (2005)—albeit with the non-trivial addition of complex scalars. It is a network of multiplicative (scalar) relations, covering a vector space that projects into Hermitian territory ($\pm Z$/NP within the recursive core of the graph, possibly terminating into $\pm I$/AP) or otherwise ($\pm C1$/PP within the recursive core of the graph, possibly terminating into $\pm C2$/VP). Needless to say, assigning categorial features [+N, −V] or a corresponding Chomsky matrix does not distinguish all possible nouns there could be. But the implied algebra is meant to combine with other cognitive systems (vision, audition, motoric, etc.) for nuances arising in the vector space—still by way of matrix operations (structure-preserving tensor products). If this is the case, the syntactic scaffolding should still be what it is: the algebraic foundation of the vector space where syntax lives, no more—but no less either. The objects in our group are useful in relating to the derivational workspace where syntactic operations are understood vectorially. The issue is how that space corresponds to neurophysiological observables.

Suppose we presume a Hebbian approach to real quantities, as customary in connectionist models summarized in Smolensky and Legendre (2005)—which numerical weights purport to reflect. This is straightforward for a class of matrices

34 I thank Ellen Lau for useful discussion of these matters, regarding the possible relevance of active maintenance.

in (20) of a sort called Hermitian, all of whose eigenvalues are real[35].

Rieffel and Polak (2011) chapter 4.3 reminds us how Hermitian operators define unique orthogonal subspace decomposition, understood as their own eigenspace decomposition, which stands in a bijective correlation with that particular operator. As a consequence, Hermitian operators describe measurements in the system. The intention is to presume the same underlying notions, then relate complex entries in a transition matrix to these dynamics, given the FFT.

Such a *transform* is relevant to some temporal slice x of a wave w, for instance carrying a vowel for which we want to process vowel formants. The wave function describing w has solutions involving trigonometric expressions with complex variables. Again, the smaller x gets, the harder it gets to identify w, as we are making the wave package smaller, hence it gets harder to understand its aggregative nuances (w being approximated by integrating a sum of sinusoidal waves, less accurately as x shrinks). That uncertainty directly underlies a variable correlation, which can be interpreted conservatively (in cognitive models sensitive to these), or radically, if the brain's wetware is somehow sensitive to quantum effects. While in the classical view, w's states simply evolve in time, in a vector (Hilbert) space, w's time evolution is abstractly expressed *via* the matrices crucially involving complex entries, in that respect differing slightly from those in Smolensky and Legendre (2005)[36].

In either interpretation of the FFT, decoupling a wave state from a measurable state boils down to the idea that the Hermitian projections in the Jarret graph (NPs, APs) are the observable entities; but while the other projections (VPs, PPs) still exist for the architecture to make sense, they either are harder to pin down (in the conservative interpretation) or do not materialize (in the radical view).

That, of course, can be the wrong assumption to make—just as the entire algebraic translation of Chomsky (1974) *via* the Fundamental Assumption, or even the Varro/Chomsky generalizations, could be wrong. But if on track, the hypothesis has a direct consequence for the neurophysiological tracking of punctual vs. distributed features, only Hermitian categories like $\pm Z$/NP or $\pm I$/AP can be punctual in the desired sense and identifiable in brain events, while others like $\pm C1$/PP and $\pm C2$/VP should correspond to distributed interactions. Right or wrong, the purported differences should be (relatively) simple to spot, starting with the identification of rigid $\pm Z$/NP entity-types as punctual (measurable) as compared to the descriptive types associated with $\pm C2$/VP, or similar considerations for other domains (consonants/vowels, aspect, etc.). If the program is on track, the distributed pattern should show up, more generally, in A-movement transformations (like passives) and similar interactions.

Another way of stating the overarching goal of this program is that, beyond formal virtues that one may argue for in the computational/representational part of the EEF equation of the present hypothesis, regarding the labeling algorithm, its neurobiological consequences are a complementary duality for which we expect different neurophysiological signatures. By the system's postulates, only phrases like NP (or other Hermitian projections) correspond to a primitive semantic type; VP (or the Varro/Chomsky lexical items, understood as operators) do not correspond to one such observable, regardless of algebraic reality. This is the spirit of the account, which has consequences in terms of the ways to identify each category type. Only those with real determinant labels are expected to correspond to ballistic gestures in any way one can characterize the notion, when appropriately generalized beyond phonetics to other levels of representation. In turn, categories with complex determinant labels correspond to distributed realities, in the realm of tetanization, active maintenance, and like-notions.

The interest in tetanization thus seems two-fold. Descriptively, because it involves an engaged eventuality that lasts for so long as the process is involved, which may be arbitrarily large and suddenly ceases, once the engaged muscle groups discontinue their engagement. Second, at a more explanatory level, forms of tetanization would seem to involve nuanced synaptic mechanisms beyond the familiar local ones. If we are modeling Hebbian plasticity through a representation involving real quantities in the matrices that we are exploring, are the complex quantities to be related to heterosynaptic dimensions, in particular for tetanization or putative extensions/correlations into active maintenance?

As Smolensky and Legendre (2005) emphasize, the beauty of linear algebra is its ability to express both differential equations and a certain symbolic representation in underlying eigenfunctions. In that program, as in the present variant with MP presuppositions about labeling algorithms, this could constitute a translation between the abstract(er) computational/representation formulation and its neurobiological consequence in terms of familiar oscillators. It may be worth isolating neurophysiological signals for global wave-states associated with tetanization and active maintenance, in contrast to less dynamic counterparts that may collapse into punctual gestures and identified categories, among which one hopes to be able to fix rigid designators. This may give us an achievable way to seek a testable correlation between formal theories of the mind and in principle measurable theories of the brain.

6. Conclusion

This volume invited contributors to think about whether theoretical syntax can effectively guide neuroscience research, in the context of what linking theories are necessary to facilitate the prospect. I believe it can, if we are ready to analyze existing syntactic theories at an abstract enough level, with the help of linear algebra.

35 The Hermitian matrices in (20) are easy to identify by noticing how their entries (corresponding to eigenvalues) are all real. Readers can verify the following simple formal facts:

(i) The trace (sum of diagonal elements) of a Chomsky matrix falls within $\pm 1 \pm i$, while it is zero for Pauli's Z and its negative $-Z$.

(ii) The determinant (product of the eigenvalues) of a Chomsky matrix is $\pm i$; while it is -1 for Z and its negative $-Z$ (here seen as twin projections of $C1/N$.

(iii) The characteristic polynomial of both Z and $-Z$ is $x^2 - 1$; for the Chomsky matrices we have:
nouns: $x^2 - (1 - i)\, x - i$; verbs: $x^2 + (1 - i)\, x - i$; adjectives: $x^2 - (1 + i)\, x + i$; adpositions: $x^2 + (1 + i)\, x + i$.

36 This can describe the fundamentals of the wave behavior in a system involving quantization, with relevant states being eigenstates of relevant operators, as presumed in quantum computation.

Standard systems, based on classical information theory, have mappings between syntactic representations and semantic correlates that are as easy to state as they are hard to map to identifiable neurophysiological correlates (mapping is cheap and one arbitrary decision as good as any other). The present system has examined formal properties *for underlying features*, involving complex scalars correlated with real ones. It seems to me an empirical question whether the language faculty presents such scaffolding features; but if it does, the task of identifying the brain correlates may be slightly less daunting, presuming they correspond to observables of the *punctual vs. distributed* sort. The syntactic model presented here presumes M and a corresponding labeling algorithm, which one can state in the algebraic fashion sketched above. The jury of time will decide whether the translation analyzed here is fanciful or, instead, relevant to our quest for a mapping hypothesis between T_M and T_B, the old chestnut of mind and body from a perspective aided by a math lens. The fact that Pauli's group is the foundation of quantum computation adds a curious dimension to this enterprise, with consequences well-beyond anything I could possibly reflect on in this context. But without even presuming anything at all in that realm, it seems worth exploring whether this hypothesis helps us constrain the search. For that is its main goal, beyond deducing some syntactic phenomena. If the theory is right, the familiar (growing) "particle Zoo" of syntactic cartographies and feature ontologies may need to be rationalized within algebraic projections as discussed here, only a handful of which (the Hermitian ones) are measurable in any punctual sense, the remaining categories then predicted to be as distributed as any corresponding wave would be. That would seem to be in the spirit of the remarkable Chomsky (1974), by attempting a rigorous instantiation of some of its presuppositions.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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How (not) to look for meaning composition in the brain: A reassessment of current experimental paradigms

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When we use language, we draw on a finite stock of lexical and functional meanings and grammatical structures to assign meanings to expressions of arbitrary complexity. According to the Principle of Compositionality, the meanings of complex expressions are a function of constituent meanings and syntax, and are generated by the recursive application of one or more *composition operations*. Given their central role in explanatory accounts of human language, it is surprising that relatively little is known about how the brain implements these composition operations in real time. In recent years, neurolinguistics has seen a surge of experiments investigating when and where in the brain meanings are composed. To date, however, neural correlates of composition have not been firmly established. In this article, we focus on studies that set out to find the correlates of linguistic composition. We critically examine the paradigms they employed, laying out the rationale behind each, their strengths and weaknesses. We argue that the still blurry picture of composition in the brain may be partly due to limitations of current experimental designs. We suggest that novel and improved paradigms are needed, and we discuss possible next steps in this direction. At the same time, rethinking the linguistic notion of composition, as based on a tight correspondence between syntax and semantics, might be in order.

KEYWORDS

composition, compositionality, semantics, experimental paradigms, brain, methodology

1. Introduction

Linguistic communication rests on our capacity to combine the meanings of morphemes and words into complex semantic structures. This basic property of language has been a central concern in linguistics for decades. More recently, it has attracted the attention of neurolinguists, as the need to understand its neurobiological underpinnings has become pressing. Research on "composition," "unification," "combinatorics," or "integration" is now common in cognitive neuroscience. Yet, the mechanisms by which meaning is composed in the brain remain at present elusive: neural correlates of composition, invariant across experiments using different paradigms and methods, have not yet been established. The delay in our understanding of composition in the brain may partly stem from limitations inherent in the paradigms used so far: we will argue that *none of them currently affords the direct comparisons between conditions that could reveal a correlate or signature of composition*. As we review these paradigms, we will identify a number of requirements that future experiments should meet to achieve that goal.

But how should composition be defined? At the computational level (Marr, 1982; Baggio, 2018) in formal semantics and adjacent fields, composition is the operation that, for any given complex expression *E*, takes as input *E*'s immediate constituent meanings and *E*'s constituent structure and outputs *E*'s meaning (Heim and Kratzer, 1998). Compositionality is the idea that there is a strong parallelism, or one-to-one correspondence, between the operations that build syntactic structures and meaning composition: each application of meaning composition mirrors the application of syntactic structure-building operations. In the Minimalist Program, Merge is used to derive hierarchical constituent structure by recursively forming sets of syntactic objects in pairs (Adger, 2003). In standard versions of formal semantics, composition amounts to the "saturation" of "unsaturated" meanings (e.g., a verb by its arguments) *via* the operation known as Functional Application, where a function is applied to arguments of appropriate type (Heim and Kratzer, 1998). All these operations are characterized *atemporally* in any formal system that strives to model the syntax and semantics of a language. At Marr's (1982) algorithmic and implementational levels of analysis, instead, these operations are modeled as *processes* unfolding in time. Our focus is on studies investigating *local* composition of *linearly adjacent* functional or lexical items, where there is a direct correspondence between logic and time, or between the deployment of composition at the computational level and its algorithmic and neural execution. This correspondence becomes more complex with non-adjacent constituents, which pose specific problems for theories and experiments. Moreover, our focus will be on on-line language *comprehension*, not on production: little is known (and perhaps can be known experimentally) about whether and how meanings are *composed* during early stages of conceptualization and message generation.

The question of the neural bases of composition and Compositionality has only recently been brought to the foreground of research. But this move did not provide the hoped-for advancements: the way meaning is composed in the brain remains an unsolved problem (Pylkkänen, 2019). Current experiments have not been based on paradigms that reliably vary the presence vs. absence of composition. At a minimum, the field has not benefited from enough discussion on whether accepted and presently used paradigms achieve the intended aims. This paper tries to fill this gap. We will not focus so much on the *results* of each study: those cannot be confidently interpreted unless the validity of paradigms is thoroughly assessed. Published research may report spatio-temporal activity that differs between conditions, but those effects may not entirely reflect the processes of interest, *if the baseline conditions cannot fully prevent composition*. Furthermore, it is not obvious that limitations of current paradigms can be mitigated by using higher-resolution neural recordings or more advanced methods for analyzing data. Progress is needed on several fronts simultaneously: here we concentrate on the paradigms front.

We should emphasize that the same paradigm or design may be inadequate for studying composition and perfectly suitable for other aims, for example the identification of brain signatures of syntactic or semantic processing complexity. On the one hand, this implies that some paradigms are "almost good enough", in that they successfully target processes closely associated with composition. On the other hand, this should remind readers that our aim is not to disqualify certain paradigms, designs, studies, or research programs *as such*, or even as viable approaches to the experimental study of syntax and semantics in the brain, but only and specifically as they relate to syntax-driven meaning composition, as defined above. We will thus discuss studies that manipulate the inputs of composition (constituents meanings and syntax) and ask whether the chosen conditions are adequate to identify, upon subtraction or comparison of neural responses, a correlate or signature of meaning composition. Even if a paradigm was not originally or primarily intended to study composition, we can still ask whether it *can be leveraged* to do that.

Research on composition makes the rather plausible assumption that, for meanings that *are* regimented by Compositionality, we should be able to identify experimentally neural events that instantiate composition in comparison to conditions where the requirements of composition are *not* met, because constituent structure or meaning cannot be derived or the meanings of the parts are unavailable. The challenge is indeed to utilize control or baseline conditions that can prevent the system from engaging in composition. Syntactic and semantic processing are however correlated. One problem for isolating composition in the brain is that studies that vary the structure of a stimulus tend to vary its meaning as well (Pylkkänen, 2019), and covarying neural signals can be difficult to disentangle. A second challenge is that composition is correlated or co-occurring with *other* processes, including non-strictly-compositional processes, like conceptual combination, pragmatic processing, inference etc. (Baggio et al., 2016). Thirdly, linguistic theories and processing models do not yet fully agree on the steps by which structure and meaning are built, and linking hypotheses that can effectively connect levels of analysis and guide experimental research are scarce (Baggio et al., 2012a; Pylkkänen and Brennan, 2019; Baggio, 2020).

Most paradigms that have been used to study compositional processes vary the presence or absence of syntax or lexical semantics. By subtracting the compositional and baseline responses, they attempt to isolate only that which differs between the two: neural events associated with syntax-driven meaning composition. We discuss paradigms that use this approach (Section 2) or that exploit particularities of languages to vary semantics while keeping structure constant or vice versa (Section 3). Although we take structure to be an essential ingredient in meaning composition, studies that attempt to isolate composition should look not just at structure building *per se*, but at the derivation of *meaning* guided by structure. Thus, we will also consider studies investigating syntactic composition that used stimuli with compositional meaning (e.g., Pallier et al., 2011). Instead, experiments on syntactic structure in designs where meaning is absent, such as artificial grammars, will not be considered, along with studies using classical semantic or syntactic violations (e.g., Ni et al., 2000; Friederici et al., 2004). These designs are not suitable for isolating syntactic or semantic composition. They include well-formed sentences where semantic or syntactic constraints are violated on single words, but no comparisons that can reveal syntactic or semantic composition. Furthermore, the brain might still attempt to derive meaning in anomalous sentences, even though that meaning may not be licensed by the structure of the input or may conflict with conceptual or world knowledge or pragmatic constraints (Pylkkänen et al., 2011). Violations may also trigger repair mechanisms, after which composition could theoretically still apply.

2. The beaten path: Three classical paradigms

2.1. Scrambling linear order

Sentences are not linear sequences of words, but recursive, hierarchical combinations of words and phrases. One widely used paradigm compares syntactically well-formed and meaningful expressions with stimuli where the linear order of words is *scrambled*. This manipulation is assumed to prevent the formation of syntactic structures at all levels of the hierarchy (phrases, clauses), thus disrupting compositional operations. Experiments using this approach can be separated into two groups, based on the "size" of the linguistic structures used for comparison: sentences or narratives.

2.1.1. Well-formed sentences vs. lists of words

One type of paradigm compares well-formed sentences with word lists where the linear order is broken, and thus syntactic hierarchies and complex meanings cannot be formed (Hashimoto and Sakai, 2002; Kuperberg et al., 2000). This paradigm would seem to target Compositionality directly: the meaning of a sentence is not just given by the meanings of constituents; syntactic structure plays a role, too. One assumption behind this paradigm is that lists and sentences only differ in one respect: syntactic structure. As we will see in this section, however, that assumption does not always hold.

This paradigm has been used in combination with other baselines, such as pseudoword sentences ("Jabberwocky") and pseudoword lists, to be discussed below. Word lists and scrambled sentences are used in fMRI studies to identify broad patterns of activation for language processing (Fedorenko et al., 2010) and isolate specific functional components of language (e.g., syntactic and semantic processing). In these studies, fully well-formed meaningful sentences are compared either to scrambled versions of the same sentences, where the same content and function words are presented in random order, or to lists of words not present in the original sentences. The assumption is that processes engaged at the single word level (e.g., lexical retrieval) are equally present in lists and sentences, so subtraction (sentence–list) will isolate neural responses that differ between conditions, such as a putative neural correlate of syntax-driven composition. Across studies, there is variability in how baseline conditions with word lists are built: as we will see soon, this is indirect proof of the challenges that arise when constructing stimuli in this paradigm.

Sentences compared to unstructured lists involve the construction of sentence structure *and* meaning. Some studies have thus included manipulations of meaning to tease them apart. Vandenberghe et al. (2002) used PET with a blocked design comparing sentences to lists to determine the contribution of syntax to composition. The lists used scrambled content and function words from the sentences. Similarly, Humphries et al. (2006) ran an fMRI study using semantically congruent sentences (1a) and lists (1b):

(1) a. The man on a vacation lost a bag and wallet
b. On vacation lost then a and bag wallet man then a

Both studies used semantic manipulations to disentangle compositional semantics from syntax. Semantically "random" sentences (1c) were compared with semantically "random" lists (1d); from Humphries et al. (2006):

(1) c. The freeway on a pie watched a house and a window
d. A ball the a the spilled librarian in sign through fire

The incongruent condition (1c) is intermediate between a congruent sentence and a list: it has structure, but meaning is deviant. Incongruent sentences should control syntactic structure and lexical retrieval, but differences related to contextual activation of specific lexical items still exist between these conditions. Further, plausibility or meaningfulness manipulations may not prevent composition. Semantically anomalous sentences used in these studies appear felicitous up to the first few words, allowing participants to initially compose meaning ("Youths resented a sketch of the forest"). The results indicate that a subset of regions active for sentences is also active for anomalous sentences and lists, as if the brain engaged in composition in all conditions, albeit possibly to different extents or at different positions across items.

Goucha and Friederici (2015) compared well-formed and meaningful sentences (2a) with well-formed incongruent sentences (2b) and scrambled lists of unrelated words (2c):

(2) a. The complexity of the regulations had shocked the unhappy kingdom
b. The vicinity of the constipation had ironed the uncanny wisdom
c. Vicinity the of had constipation wisdom ironed uncanny the

In Goucha and Friederici (2015), lexical information is matched across sentences and lists. To reduce the risk of incidental syntactic structure building in word lists, Humphries et al. (2006) created lists by randomly sampling function words from the stimulus set and by replacing them in sentences before shuffling their word order. Lexical content cannot be matched exactly, but randomly picked function words might be less likely to combine with the given content words. Even so, this is unlikely to fully block syntactic processing.

Another scrambling approach was used by Kaufeld et al. (2020):

(3) a. [Bange helden] [plukken bloemen] en de [bruine vogels] [halen takken]
[*Timid heroes*] [*pluck flowers*] *and the* [*brown birds*] [*gather branches*]
b. [helden bloemen] [vogels takken] de en [plukken halen] [bange bruine]
[*heroes flowers*] [*birds branches*] *the and* [*pluck gather*] [*timid brown*]

They found increased neural tracking, at the phrase frequency, for sentences (3a) vs. lists (3b), which suggests the brain is building hierarchical structure for sentences but not for lists. This could be taken to indicate that meaning composition too is happening only for sentences, tracking hierarchical structure. But stringing together locally words from the same category in lists could lead to compounding attempts (N-N), or could engage other syntactically viable modes of combination (e.g., adjective stacking, "bange bruine"). This issue is not specific to this study, but applies widely to lists paradigms. Composition may then occur in both sentences and lists, at least locally.

Another variant of this paradigm disrupts syntactic structure *parametrically*, resulting in conditions with different degrees of scrambling. Pallier et al. (2011) studied the neural mechanisms of hierarchical structure building using stimuli with five levels of scrambling. These varied in the size of the constituents, ranging from a full sentence (4a) to a word list (4f), with lists of constituents of different sizes in between, 6 to 2 words, (4b) to (4e):

(4) a. I believe that you should accept the proposal of your new associate
b. [the mouse that eats our cheese] [two clients examine this nice couch]
c. [mayor of the city] [he hates this color] [they read their names]
d. [solving a problem] [repair the ceiling] [he keeps reading] [will buy some]
e. [looking ahead] [important task] [who dies] [his dog] [few holes] [they write]
f. thing very tree where of watching copy tested they states heart plus

As constituents were extracted from the sentence condition and concatenated randomly, lexical material was matched across conditions, but not within each items set. Activation was modulated by constituent size in the left superior temporal sulcus (STS) and inferior frontal gyrus (LIFG partes triangularis and orbitalis). In a replication study, Shain et al. (2021) suggest that these effects may not reflect syntactic structure building, but the fact that shorter constituents may not fully engage the language network. Larger chunks may then be easier to recognize by the language network as stimuli to be processed.

Parametric variation of constituent size can be a way of overcoming the poorer temporal resolution of BOLD fMRI and can be used to track how composition unfolds step by step as structure and meaning are built. However, as noted by Grodzinsky et al. (2021), these designs are not without issues. The conditions do not form minimal pairs: e.g., there are additional differences in category labels and number of structural units between them. A similar study is Matchin et al. (2017), who aimed to dissociate the effects of bottom-up syntactic computations from those of top-down predictions, by comparing lists of words ("rabbit the could extract protect") to lists of two-word phrases ("the fencer the baby the bill") and full sentences ("the poet will recite a verse"). Zaccarella et al. (2017) matched as much as possible semantic content between conditions, comparing sentences ("The ship sinks") to prepositional phrases that contained a matched noun ("on the ship"). The word list baseline contained a further control measure: the nouns in the lists were in the same positions as in the sentence or phrase ("stem *ship* juice"; "leek mouth *ship*"). Matchin et al. (2017) and Zaccarella et al. (2017) find effects in the left IFG and posterior STS (pSTS) for syntactic structure building, but only the former study reports effects in left pSTS for sentences and phrases.

Mollica et al. (2020) compare in an fMRI study well-formed sentences (5a) to scrambled sentences with 1 swap (5b), 3 (5c), 5 (5d) or 7 swaps (5e), and a list of content words:

(5) a. on their last day they were overwhelmed by farewell messages and gifts
b. on their last day they were overwhelmed by farewell *and messages* gifts
c. on their last *they day* were overwhelmed *farewell by* and *messages gifts*
d. on their last day *were overwhelmed they farewell messages by gifts and*
e. their last *on they overwhelmed were day farewell by* messages and gifts

The novelty here is that word order is disrupted, but the message can still be recovered. A second experiment included a condition where scrambling was so severe that syntactic and semantic relations between words could not be established:

(5) f. last day farewell gifts on were and they by they overwhelmed message.

The results show that, if dependencies between words can be recovered, linear order has little impact on processing: activation levels were similar across conditions, irrespective of scrambling. The exception is (5f), where scrambling was such that words cannot form dependencies: here activation levels were lower, closer to the level of content word lists.

This study is a reminder of the importance of carefully constructed baseline and control conditions. When scrambled words are linearly close to other words with which they can plausibly enter a dependency relation, there are no differences between the baseline and compositional conditions. One possibility, compatible with Mollica et al.'s interpretation of these results, is that scrambled sentences (5b–e) cannot prevent extraction of meaning from input: the brain is quite "aggressive" in its urge to compose. There is another lesson one could draw here. The extent to which intepretation requires (hierarchical) syntactic structure is open to question (Culicover and Jackendoff, 2006; Baggio, 2018, 2021; Nefdt and Baggio, 2023). Participants might use linear order as a proxy for syntactic structure,[1] or extract meaning without (fully) reconstructing structure. If participants seek to compose meaning even in the scrambled conditions, either they do not need syntactic structure to compose or they are trying to fix the disrupted mapping between syntax and word order.

1 Note that linear order feeds in a systematic way off of structure, but it is not completely determined by it. Different languages have different base orders and tend to allow for variation in word order for the same message. Thus, linear order is not an exact proxy for syntactic structure.

In most fMRI studies using this paradigm, activation levels are averaged over the whole sentence and are compared with the average signal from word lists. Because of the slow temporal evolution of the BOLD response, these studies cannot zoom in on syntactic or compositional processes at specific points in a sentence, but can only indirectly associate composition to regions that activate more with the presence vs. the absence of structure, a binary variable that applies to the entire stimulus (Matchin et al., 2019a). Composition, however, is a *time-sensitive process* that may not occur in the same form at each word (there may be differences for optional vs. obligatory elements, function vs. content words etc.), that may not happen at every single word (if certain constructions imply storage of material, e.g., with long-distance dependencies), and that may be revised at subsequent processing stages (Baggio et al., 2008; Baggio, 2018). A fine-grained map of composition operations, as realized in the brain, may only be obtained from measures with sufficient temporal resolution and with experimental designs that harness that resolution. M/EEG have the advantage of sampling brain activity with a millisecond resolution. Hultén et al. (2019) use MEG to compare sentences (e.g., "I like to read nice books in my spare time") to lists containing the same words as the sentences, but in a scrambled order. For every word in the sentence, they found activity around 400 ms in the left posterior temporal cortex (LPTC), left inferior frontal cortex (LIFC), and left anterior temporal lobe (LATL). Fedorenko et al. (2016) used cortical-surface EEG (ECoG) with lists and sentences. They observed a monotonic increase of gamma power over frontal and temporal areas as the sentence unfolded. For lists, this was only seen until the third word, after which activity dropped, suggesting that participants may initially attempt to process lists much as they do sentences. Their results also show increased gamma activity for word lists relative to Jabberwocky and nonword conditions, suggesting that composition might be engaged in that condition too, as constituents in word lists may still be formed. Using ECoG, Nelson et al. (2017) compared sentences vs. scrambled lists and found high gamma decreases for words closing syntactic phrases. These studies point to possible gamma-band signatures of structure building or syntax-driven composition (but see Murphy, 2020 for a different account). However, word lists do not allow researchers to exploit the superior temporal resolution of M/EEG: as word order in lists is disrupted, one cannot compare the same word across conditions at any given time point while controlling for properties of the left context. Independent improvements of this paradigm would therefore be needed to fully take advantage of better recording resolution or advanced data analysis methods.

In these experiments, lexical material is matched between the items being compared but the presence of function words may still trigger structure building attempts also in lists, as suggested by Zaccarella et al. (2017). Their meta-analysis shows function and content words in lists can activate language regions, e.g., the left IFG. Affixes and function words carry grammatical information and can therefore guide syntactic processing. In an fMRI study of the neural correlates of syntax and semantics, Friederici et al. (2000) compared spoken German sentences (6a) to word lists (6b):

(6) a. Die hungrige Katze jagt die flinke Maus.
The hungry cat chased the fast mouse.
b. Der Koch stumm Kater Geschwindigkeit doch Ehre.
The cook silent cat velocity yet honor.

They removed function words and inflectional morphology from lists and omitted verbs: German word order can make verbs within lists trigger syntactic processing. Still, their lists are considerably less diverse lexically than sentences. They reported activations for sentences relative to lists in the bilateral superior temporal gyrus (STG). This region has been associated with phonological processes. Given the differences in length or duration of words in lists (only content words, minus verbs) vs. in sentences (content and function words), it is difficult to establish whether the STG effect here is due to composition or to processing of phonological or auditory properties of stimuli. A similar concern applies to recent work, such as Branco et al. (2020), who also used lists with only content words as baselines. They find activation for sentences relative to word lists across left frontal and temporal areas, but this result may include any area sensitive to the distinction between function and content words, as opposed to combinatorial processes more specifically.

A possible approach to isolating composition would be to remove confounding variables by modifying the stimuli in a stepwise fashion. Humphries et al. (2005) compare spoken sentences (7a) to unstructured lists with and without prosodic cues. The lists served as a baseline and could contain function and content words (7b) or only content words (7c):

(7) a. The man was looking forward to an upcoming road trip in his expensive new car.
b. That the in the wearing students the blonde expensive south up waits in performing the ate.
c. Bank calm school bathtub workers home car tambourine neail waill hat beach umbrella street head.

Permuting the words within each sentence would run the risk of accidental composition: semantically related words might prompt speakers to reconstruct a meaningful message, as was noted by the authors. They thus randomly picked words from the sentence set for scrambling, keeping the stimulus length and number of syllables constant within items. The conditions were matched lexically over the entire set, but not for each item or each sentence position. The left anterior STS, toward the middle temporal gyrus (MTG), was active for sentences regardless of prosody; the left posterior STS was active for sentences with list prosody; the posterior bilateral STS showed a prosody*structure interaction.

Lists and sentences are difficult to match in all relevant respects except for composition. Law and Pylkkänen (2021) embedded lists of nouns ("lamps, dolls, guitars") into sentences (8a) or lists (8b) in an MEG study aimed at isolating correlates of syntactic composition:

(8) a. The eccentric man hoarded lamps, dolls, guitars, watches and shoes
b. Forks, pen, toilet, rodeo, lamps, dolls, guitars, wood, symbols, straps

Their results show increased activity in the left inferior frontal cortex at 250–300 ms, at 300–350 ms in the LATL, and at 330–400 ms in the left posterior temporal cortex for lists in sentences relative to lists in lists. This design affords better control over local syntactic and semantic context, and the use of bare plural nouns may help prevent N-N compounding in lists. However, the conditions are different beyond the immediate local context: lists do not include any function words, and content words before critical words differ between conditions, which might impact processing complexity and preactivation. Additionally, as noted by the authors, a word's meaning in a sentence could differ from the same word's meaning in a list.

2.1.2. Composition beyond sentences: Structured narratives vs. scrambled sentences

Experiments using single sentences may be argued to lack the ecological validity needed to draw inferences about how compositional machinery is used in everyday life (Hasson et al., 2018). We rarely communicate in isolated utterances: the messages that we convey often span multiple sentences. Recent studies have thus used multi-sentence narratives, typically presented in the auditory modality as naturalistic speech. Narratives have been compared to lists of scrambled words from the same story, to lists of words matched in lexical variables with words in the story, or to lists of unrelated sentences (Mazoyer et al., 1993; Xu et al., 2005; Brennan and Pylkkänen, 2012, 2017; Brennan et al., 2012). Lerner et al. (2011) compared brain responses to stories in the auditory modality with scrambled versions at different levels of structure: word, sentence, and paragraph, plus a condition with the story played backward. Using structured narratives results in more ecologically valid conditions and increases the variety of expressions investigated. But these studies also use lists of words or sentences as baseline conditions, incurring the problems raised above. Further, the size of the stimuli makes it difficult to zoom in on local composition: interpretation of most words in narratives is influenced by the discourse model built up to that stage, engaging processes beyond composition (Baggio et al., 2016; Baggio, 2018).

2.1.3. Problems with lists: Interim summary

Some paradigms have tried to align experimental and baseline conditions by controlling lexical frequency, length, and word class across sentences and lists, by scrambling words from the same sentences, by combining words from different sentences in the stimulus set, by leaving out function words, or by matching local contexts while varying aspects of global contexts. Such strategies may not always achieve minimality or precise matching of conditions (Grodzinsky et al., 2021).[2]

Beyond minimality, the potential risk of accidental syntactic or semantic composition in lists always looms over the interpretability of experimental results, particularly when the words used in lists are drawn from the critical sentences and shuffled in random order. An inspection of the stimuli used in many studies reveals that phrase level dependencies can sometimes still be formed (Mollica et al., 2020). Matchin et al. (2017) too point this out as a possibility in their list condition. The task used might encourage participants to impose syntactic structure on unstructured lists (Matchin et al., 2017). Some studies use block designs as a remedy, but drawbacks can be habituation effects or the emergence of expectations and processing strategies. There are also further differences in sentences vs. lists that are rarely discussed, for example that sentences introduce more information to be encoded in memory. Lists could engage attention and control more than sentences, if there is an active effort to interpret the stimulus.

An additional level of complexity is introduced by the interaction of problems related to the choice of methods (fMRI vs. M/EEG) with challenges that arise from problems in the paradigms themselves. With respect to minimal pairs, one question is whether the effect of noise or variability from different lexical items is more dangerous than the addition of function words in non-composition baselines, or vice versa. In fMRI, where localization is the goal, it may be more appropriate to get rid of function words than to be rigid about matching words in each comparison. With M/EEG, the trade-off might go the other way, given the prominence in measured signals of preactivation and related effects of content words, which should then be matched as much as possible. Sentence-level comparisons, for example using fMRI, would work only if differences between lists and full sentences were spatially localized on a "macro" level. Even then, fMRI's lack of temporal sensitivity still largely threatens non-minimal paradigms, if the goal is to isolate basic composition: the effects of pure composition will interleave with other linguistic operations and smear out over the total fMRI signal over the course of a sentence. This problem is exacerbated with longer discourses. Our assessment of studies using lists, scrambling, or constituent chunking is summarized in Table 1. Anomalous sentences and lists with function words are, in our view, the most problematic. Lists without function words may reduce chances of accidental composition, but the resulting contrasts are less minimal compared to lists with function words and scrambled sentences. In terms of minimality and naturalness, scrambled sentences are superior to lists with function words.

2.2. The Jabberwocky alteration: Form without content

Lists of words aim to disrupt linear order and thus prevent composition. However, this type of stimulus cannot be used to dissociate meaning and grammar: sentences and lists of words differ both in structure *and* compositional semantics (Grodzinsky et al., 2021). Differences between the two conditions will then reflect both aspects of composition.

One type of design, meant to dissociate syntax from semantics, relies on baseline stimuli that are devoid of lexical meaning, but still grammatical. Jabberwocky consist of phono- and morphotactically and grammatically well-formed strings, lacking content. Structure building is assumed to proceed unimpeded, but meaning composition is blocked by the unavailability of constituent meanings. In typical Jabberwocky experiments, all content words are replaced with phonotactically licensed pseudowords, maintaining all function words and affixes ("The gar

2 We define a "minimal pair" as two conditions that only differ in the variable of interest: e.g., conditions that only differ in that one involves composition and the other does not or where the mode of composition is different. An exact matching between conditions might prove impossible at the level of the stimulus, but a close matching might still obtain if the processes in the two conditions are identical except for the one of interest. Examples of steps in this direction are discussed in Section 3.

TABLE 1 A summary of limitations associated with each of the paradigms discussed in Section 2 with a rating (low, medium, high) of how problematic we believe each limitation is for the purposes of isolating the neural correlates of meaning composition.

Limitations	Scrambled sentences	Anomalous sentences	Lists with function words	Lists without function words	Constituent chunking	Pseudoword sentences or Jabberwocky	Minimal phrases
Comparison is not minimal	Low	High	Medium	High	High	High	Medium
Risk of accidental composition	High	High	High	Low	Medium	Medium	Medium
Lack of naturalness	Medium	Medium	High	High	Medium	High	Medium
Total problematic	Medium	High	High	Medium	Medium	High	Medium

A total average rating is also assigned to each paradigm.

was swabbing the mume from atar"; Fedorenko et al., 2016). The pseudowords are usually derived by replacing phonemes in real words while making sure that the resulting pseudowords do not exist in the given language. In Jabberwocky, syntactic constituents and dependencies are thus maintained in the absence of meaning. Some studies match low-level properties of Jabberwocky to real language by controlling variables such as bigram frequency, syllable length, and phoneme length (Heim et al., 2005; Humphries et al., 2006; Branco et al., 2020). By comparing a normal sentence (e.g., "The poet will recite a verse") with a Jabberwocky version matched in syntactic structure, but not in content (e.g., "The tevill will sawl a pand"; Matchin et al., 2017, 2019a), one can reveal brain activity that reflects processes necessary to derive compositional meaning.

There are however differences in how Jabberwocky and pseudoword sentences are used across studies. Friederici et al. (2000) maintain morphological and capitalization rules of German to give Jabberwocky the "feel" of German: "Das mumpfige Fölöfel föngert das apoldige Trekon". In addition to pseudowords, Fedorenko et al. (2016) used a low-level condition with strings of "nonwords" (e.g., "Phrez cre eked picuse emto pech cre zeigely"). This condition is meant to control for low-level orthographic processing in the absence of lexical processing and composition. Sometimes pseudowords and function words are scrambled within a sentence (e.g., "rooned the sif into lif and the and the foig aurene to"). The normal sentence vs. Jabberwocky sentence contrast is used to identify the effects of compositional semantics when structure is held constant (Röder et al., 2002), while the Jabberwocky sentence vs. Jabberwocky lists contrast is used to isolate syntactic structure building in the absence of meaning (Goucha and Friederici, 2015). This is seen as a viable strategy, if the goal is to dissociate syntactic from semantic processing (Pylkkänen et al., 2011). But as with word lists, Jabberwocky and pseudowords, let alone nonwords, raise concerns about the minimality of the stimuli compared; for example, some phonological and lexical variables cannot be measured and matched between the two conditions.

The question of whether specific areas of the language network are sensitive to syntactic structure, word meanings, and their interactions is often debated in the field (Fedorenko et al., 2012, 2020; Hagoort and Indefrey, 2014). Several studies used pseudoword sentences vs. unstructured pseudoword lists to disentangle syntax and semantics in the brain (e.g., Fedorenko et al., 2016; Matchin et al., 2017). Branco et al. (2020) use pseudowords lists, lists of content words, real word sentences, pseudoword sentences, and a non-linguistic baseline with symbols matched in length and visual features to the linguistic stimuli. A similar design is used by Humphries et al. (2006), who compared conditions assumed to be minimally different in the presence or absence of syntax or semantics. In addition to normal sentences (1a), incongruent sentences (1c), and lists (1b), they used pseudoword sentences and pseudoword lists containing real function words:

(9) a. The solims on a sonting grilloted a yome and a sovir
b. Rooned the sif into lilf the and the foig aurene to

Structured stimuli were compared to lists to establish a main effect of syntax: activation differences were seen in the left anterior STS. The effect of compositional semantics was derived by comparing normal sentences to incoherent sentences: these conditions both involve lexical processing, but only normal sentences result in a meaningful proposition. This contrast revealed effects in the left inferior temporal gyrus, the left STS, and the left AG. Comparisons were performed between incoherent and pseudoword sentences (with activation in left anterior, middle, posterior STS) and between normal and pseudoword sentences to determine effects of lexical processing (anterior, middle, posterior STS and MTG). The analysis was limited to temporal areas, but the results show that semantics is subserved by a wider network of areas in the temporal lobe than syntax.

Stromswold et al. (1996) used a variation of this paradigm with conditions in which only one word in a sentence was replaced by a pseudoword (10a) vs. center-embedded (10b) and right-branching (10c) sentences:

(10) a. The economist predicted the recession that *chorried* the man
b. The limerick that the boy recited appalled the priest
c. The biographer omitted the story that insulted the queen

By manipulating both syntactic complexity and the possibility of deriving compositional meaning, this study asks whether brain areas subserving syntax as opposed to semantics can be isolated. They found increased activation in LIFG for syntactically more complex sentences and in the inferior frontal gyrus, superior temporal gyrus, and supramarginal gyrus for normal sentences vs. sentences with a pseudoword.

Another experiment using pseudowords to investigate syntactic composition is Segaert et al. (2018). To minimize the effect of semantics, they used sentences where the subject is a pronoun and the verb is a pseudoword with inflectional morphology ("She grushes"). The baseline is a list of pseudowords matched in length to the sentences ("pob grushes"). The pronoun is assumed to trigger syntactic composition, whereas the pseudowords list should not. Structure building could also occur in lists, as morphological marking on the second word could allow speakers to parse the list as a pseudo-subject noun followed by a pseudo-verb. The study found increases in EEG alpha power over left fronto-temporal channels for sentences vs. lists, for the first and second words, interpreted as predictive and syntactic processes respectively (see also Hardy et al., 2023).

It could be argued that Jabberwocky still involves formal compositional semantics, even though lexical and conceptual semantics are absent. Grammatical cues could license the assignment of thematic roles toward an interpretation: e.g., "The tevill will sawl a pand" refers to an event (sawl) that will be initiated by an entity (the tevil) affecting another (a pand). This is compatible with the results of studies such as Branco et al. (2020),[3] which did not find differences in activation between real sentences and pseudoword sentences. Goucha and Friederici (2015) exemplify this observation in a parametric design. To identify areas of the left inferior frontal gyrus selectively involved in syntax and semantics, they used several types of pseudoword sentences as baselines. Their Jabberwocky sentences contained phonologically licensed pseudo-content words and real function words, with inflectional and derivational morphology (10a). They removed derivational morphemes (10b) and inflectional morphology replacing determiners with pseudowords (10c):

(10) a. The pandex*ity* of the larisa*tion***s** ha**d** zapp**ed** the *un*heggy wog*dom*.
b. The pandesteek of the larisarden**s** ha**d** zapp**ed** the enhegg**ed** fordem.
c. Thue pandesteek of thue larisarden feg zopp thue enheg fordem.

Their fMRI results show a different pattern of activation for pseudoword sentences with vs. without derivational morphology, suggestive of residual morphosyntactic processing.

Another known issue is that pseudowords, due to their resemblance to real words, might trigger a "search" in the lexicon which will return no results. This might make them more difficult to process than real words, undermining the assumption that pseudowords can serve as a baseline involving fewer/simpler processes. Iwabuchi and Makuuchi (2021) use pronounceable letter strings as placeholders for real words, adding relevant morphology to form hierarchical structures in Japanese. They also included a syntactic manipulation with sentences with the canonical SOV word order (11a), more complex OSV order (11c), as well as non-semantic sentences containing placeholders, but with the same syntactic structures as the natural sentences (11b, d):

(11) a. ranboo-na sootoku-ga daijin-o tataita. (*The wild governor hit the minister.*)
b. PP-na AA-ga BB-o V-sita. ($PP_{adjective}$ *-AA V-PAST BB*)
c. daijin-o ranboo-na sootoku-ga tataita. (*The wild governor hit the minister.*)
d. BB-o PP-na AA-ga V-sita. ($PP_{adjective}$ *-AA V-PAST BB*)

This type of design aims at dissociating syntactic from semantic processes in the brain, without using an additional condition of pseudowords and word lists. Using fMRI, they found an effect in the LATL for sentences vs. pronounceable non-sentences regardless of word order. BA44, premotor, and parietal cortices were more active to the placeholders. This latter finding might be attributed to the perceptual and/or phonological differences between placeholders and real words. The effect of syntax was less robust: activations in BA45 and pMTG were observed only before correcting for multiple comparisons.

2.2.1. Problems with Jabberwocky: Interim summary

The Jabberwocky paradigm tries to create an impoverished language, where meaning is removed but syntactic structure is preserved: the goal is to block semantic composition while keeping syntactic composition and other grammatical processes going. However, pseudoword sentences do not entirely lack compositional meaning, and function words, when present, can trigger the construction of a minimal formal semantic representation. Comparing sentences to Jabberwocky, with the purpose of isolating processes specific to meaning composition, can result in loss of signal precisely relevant to the latter process. Pseudowords and real words differ in frequency, familiarity, and the cognitive resources allocated to them, for example lexical recognition and search. Pseudoword sentences are used as part of designs also including (pseudo-)word lists, but pseudowords and lists of real words differ in their levels of salience and intelligibility, making direct comparisons difficult (Bautista and Wilson, 2016). Studies attempting to isolate syntactic and semantic components of language processing using word lists and pseudowords sentences can fail to create true minimal pairs: these conditions differ on other dimensions from sentences than just the presence or absence of syntax and semantics (Grodzinsky et al., 2021). Our assessment of studies using pseudowords sentences or Jabberwocky is provided in Table 1. Lack of minimality and naturalness of these stimuli are the main limitations and what renders these paradigms overall problematic for studying meaning composition.

2.3. Minimal phrases

Sentences involve processes that can obscure purely compositional operations. Semantic associations and other memory-based processes, conceptual combination, preactivation, prediction, and inferential, referential, and elaborative processes, among others (Baggio, 2018), contribute to meaning construction over and above composition. These processes interact with each other to ease demands on processing of downstream inputs (Bemis and Pylkkänen, 2013a; Zaccarella et al., 2017). In none of the paradigms reviewed above can composition be fully disentangled from co-occurring processes. Previous sentence-level studies have focused on delineating linguistic distinctions, such as lexicon

3 This is also the explanation given by the authors for the lack of an effect.

vs. grammar, under the assumption of large-scale differences in localization. Interpreting their results to make claims about Compositionality requires linking hypotheses on the role of syntax in composition, e.g., whether syntax is the only driver vs. one constraint among many, or whether composition differs for lexical content vs. logical syntacto-semantic relations.

In order for a compositional algorithm to be set in motion, it needs to be fed at least two elements (e.g., words) to produce the meaning of their combination. From a generativist standpoint, elements are combined in pairs. This combination then becomes an element too, to be combined with another in a further step of the derivation. The minimal phrase paradigm, by Pylkkänen and collaborators, uses two-word phrases as the main object of investigation. Bemis and Pylkkänen (2011) "truncate" the pseudowords and lists designs in order to adapt them for the study of composition in simple phrases. Their compositional stimulus was a two-word uninflected adjective-noun phrase ("red boat") to be compared to a baseline consisting of an unpronounceable letter string followed by the same noun ("xkp boat"). The noun "boat", at which the comparison is made, can enter composition in the first but not in the second condition. The use of an unpronounceable letter string, as opposed to a pseudoword, would serve to prevent composition attempts. To control for influences of the lexical material before "boat" in the two word conditions, they included non-combinatorial lists of two nouns ("cup, boat"). However, the brain is eager to extract meaning from input, and there is a possibility of noun-noun compounding in lists (e.g., a plastic or paper cup made to float like a boat). Bemis and Pylkkänen then introduce an additional task manipulation. The task required participants to compose the meaning of the two words and to check whether the combination matched a subsequent picture of a colored object (composition task) vs. read each word to verify whether one matches the picture following each trial (non-composition task). Composition only takes place at the second word, where contextual processes are minimized. This makes minimal phrases a better fit for time sensitive M/EEG methodology than other paradigms. In the auditory modality, pink noise can be used as a baseline instead of nonwords (Bemis and Pylkkänen, 2013b). Activity in the LATL, from around 200 ms from the onset of the second word, has emerged as a possible signature of semantic combination (Pylkkänen, 2019).

This paradigm combines a tightly controlled stimulus set with manipulations of the task to ensure that the recorded brain activity is related to the process at issue. For example, Bemis and Pylkkänen (2013a) compare canonical adjective noun phrases ("red boat") with reversed counterparts ("boat red") and nonword-word strings ("xhl cup", "frw red"). The key manipulation is the task, which involves a colored shape (compose) or two pictures, one of a colorless shape and one of a colored blob (non-compose): participants had to respond whether the probe matched both words. This study tested whether composition can also be deployed in ungrammatical sequences and whether it is automatic enough to be engaged even when the task does not require it. They found that the LATL is engaged in reversed sequences only when the task requires composition and with canonical word order regardless of the task. Fló et al. (2020) show that, when the task manipulation is eliminated, the effects of composition are no longer observed with EEG.

The minimal phrase experiments achieve something which has been challenging for the previously discussed paradigms: matching between conditions the word which has to be composed or not, at the position at which the neural signal is measured. The pre-critical content in non-combinatorial conditions (nonwords and nouns in lists), however, differs in several respects from the adjective used in the compose conditions. These differences might affect the signal recorded at the critical word. For example, a nonword at the start of a trial might make participants less engaged in processing the following words. At the same time, preactivations resulting from processing of a noun in lists and of an adjective in compositional trials will differ. Additionally, the two word list condition might trigger a process of compounding and thus involve composition regardless of explicit task.

Some minimal phrase studies have used multiple and different baseline conditions. Neufeld et al. (2016), Fritz and Baggio (2020, 2022), and Kochari et al. (2021) use pseudowords and nonwords to disentangle semantic and syntactic processes, and Bemis and Pylkkänen (2013a) use a reversed word order condition ("boat red"). Del Prato and Pylkkänen (2014), instead of lists of nouns, use lists of adjectives and lists of numerals as baselines, which match in category to the precritical words used in the combinatorial contexts. Graessner et al. (2021a,b) contrast meaningful two-word phrases ("fresh apple") to anomalous phrases ("awake apple") and adjective-pseudoword phrases ("fresh gufel"). In an ECoG experiment, Murphy et al. (2022) compare adjective-noun phrases ("red boat"), which are assumed to involve composition at the noun and prediction at the adjective, to adjective-pseudoword phrases ("red neub"), involving just prediction, and to pseudoword-noun phrases ("zuik boat"), which involve neither.

Some minimal phrase studies have tested how different semantic contexts interact with composition, for example how specificity of the noun modulates LATL activity (Zhang and Pylkkänen, 2015) and the impact of semantic properties of adjectives (e.g., see Ziegler and Pylkkänen, 2016; Fritz and Baggio, 2020, 2022; Kochari et al., 2021). Kim and Pylkkänen (2019) look for MEG correlates of composition in adverb-verb constructions, testing whether different classes of adverbs (eventive "slowly" vs. orientative "reluctantly") show similar LATL effects as in adjective-noun phrases. Manipulations of the precritical word target the interplay of composition and prediction, *via* the use of different pronoun types (Strijkers et al., 2019), and between composition and semantic properties of nouns, such as relationality or eventivity (Boylan et al., 2017; Williams et al., 2017). Studies have revealed early LATL responses for Adj-N phrases in the auditory and visual modalities. However, Kochari et al. (2021) failed to replicate this finding. The sensitivity of LATL to variables that syntax-driven composition should, according to theory, *not* be sensitive to (e.g., specificity) has led to the conclusion that the LATL does not perform composition, but rather *conceptual combination* (Pylkkänen, 2019). Moreover, the angular gyrus (AG) and the ventromedial prefrontal cortex (vmPFC) are involved in semantics, though they do not always activate across studies. Murphy et al. (2022) find effects of composition in portions of the pSTS using iEEG/ECoG. With EEG and minimal phrases, Neufeld et al. (2016) link the N400 to combinatorial semantic processing (Hagoort et al., 2009; Baggio and Hagoort, 2011; Baggio, 2012; Nieuwland et al., 2020), and Fritz and Baggio (2020, 2022) find and replicate P600 effects for adjective-noun composition.

The relatively tight control over experimental items offered by minimal phrases has also been used to tackle more fine-grained and theoretically relevant questions on the nature of composition. One question is whether composition in different syntactic structures or environments, such as modification and predication, is carried out by different neural processes. Westerlund et al. (2015) test the distinction between composition operations of *argument saturation* and *predicate modification* (Heim and Kratzer, 1998): the former mode of composition includes verb-noun (e.g., "eats meat"), preposition-noun ("in Italy"), and determiner-noun ("Tarzan's vine") combinations; the latter includes adjective-noun (e.g., "black sweater"), adverb-verb ("never jogged"), and adverb-adjective ("very soft"). In keeping with the standard design, each expression was compared to a nonword followed by a matched noun in order to establish effects of composition. Boylan et al. (2015) use a similar design, crossing mode of composition (argument type: "eats meat", "with meat" or adjunct type: "eats slowly", "tasty meat") with presence or absence of a verb. The baseline was non-compositional phrases in which the nonword was either the first or the second element of the sequence ("eats fghjl"/"fghjl eats"). A similar approach is used by Schell et al. (2017). Matchin et al. (2019b) matched word forms exactly within the phrases, while varying syntactic structure for noun-adjective (e.g., "the frightened boy") and verb-noun ("frightened the boy") composition. A potential confound might arise in these designs, as also noted by Matchin et al. (2019a). Whereas, a noun composed with a modifier may be interpreted as a saturated structure on its own, a noun in the object position, composing with a verb, results in incomplete syntactic and semantic structures. Boylan et al. (2015) report activity in the left AG, regardless of mode of composition, for "eats meat" vs. "tasty meat". Westerlund et al. (2015) found that the LATL is involved in argument saturation *and* predicate modification. Matchin et al. (2019b) show that activity in the left IFG and pSTS increases for verb-noun composition, while there is no difference between the two syntactic structures in AG and LATL activation.

It is worth mentioning two more studies that extend the minimal phrase paradigm. Kim and Pylkkänen (2021) use hashtags in various positions in sentences to study subject-verb composition vs. verb-object composition (e.g., "kids toss objects" vs. "### toss objects" vs. "### ### objects"). However, hashtags can discourage participants to compose meaning for the rest of the sentence, as noted by the authors. Lau and Liao (2018) used coordinated adjective-noun phrases (e.g., "sunlit ponds and green umbrellas") vs. those noun phrases separated by hashtags ("sunlit ponds ### green umbrellas") vs. Jabberwocky versions to isolate brain correlates of building coordinated structures. They find sustained anterior negative ERPs from the first word in the second phrase for coordinated constructions.

2.3.1. Problems with minimal phrases: Interim summary

The elegance and simplicity of the minimal phrase paradigm has provided fertile ground for testing core linguistic ideas with M/EEG. The main advantage of this paradigm is the control it affords over experimental stimuli, enabling the minimization of processes not strictly reflecting local combinatorics. However, minimality comes at a cost, for example a loss of naturalness or ecological validity of stimuli (Hasson et al., 2018). Full sentences may not be the most frequent type of utterance in *spoken* language corpora, but neither are NPs or VPs as used in these experiments; when those occur, they are elliptic phrases, interpretable in the context of other utterances. Most of these experiments used *written* stimuli: in written corpora disconnected noun or verb phrases may be even less common than in spoken corpora. However, one could argue that composition must take place for any given phrase, regardless of whether a naturalistic context is available. Another issue is that the baselines used in these experiments may differ from phrases in other respects than just composition. Our assessment of the minimal phrase paradigm is given in Table 1. This paradigm compares favorably to many others currently in use and is the one with the best balance between different limitations.

3. Alternative and emerging approaches

3.1. Theory-inspired and language-specific manipulations

For the paradigms just discussed, linguistic theory only covers combinatorial conditions, and possibly Jabberwocky and semantically anomalous sentences, but offers no analysis of conditions with lists of words, pseudowords, nonwords, and scrambled sentences. To bridge levels of analysis with linking hypotheses that can be evaluated empirically, both combinatorial and baseline conditions should be covered by formal theories: ideally, our theories should state why and how composition applies to some cases but not to others.

To design experiments capable of addressing composition, theoretical distinctions must be identified in the linguistics literature and stimuli reflecting those distinctions must be constructed. Consider complement coercion (Pylkkänen, 2008). Semantically, aspectual verbs, such as "begin" and "finish", require event-denoting complements (e.g., "begin the fight"), but syntactically, they may be combined with entity-denoting complements (e.g., "begin the book"): the denotation of the NP must then be coerced from entity to event, or an equivalent (e.g., inferential) operation must recover an eventive interpretation of the NP. In coercion constructions, syntactic structure is simple, but composition load varies: it is greater for entity-denoting than for event-denoting NPs (Piñango and Deo, 2016).

Baggio et al. (2010) and Kuperberg et al. (2010) compared control conditions (12a) with coercion constructions (12b) and semantic anomalies (12c). Similar conditions were also used by Pylkkänen and McElree (2007) and Husband et al. (2011):

(12) a. The journalist wrote the article
b. The journalist began the article
c. The journalist astonished the article

These studies did not use non-combinatorial baseline conditions that attempt to prevent composition, but vary processing load between two conditions that require composition, while keeping plausibility and semantic associations from the context before the critical noun ("article") as constant as possible. This strategy has also been applied to metonymic constructions (Schumacher, 2013) and aspectual coercion (Paczynski et al., 2014). Baggio et al. (2010) and Kuperberg et al. (2010) find N400-type ERP negativities. Using MEG, Pylkkänen and McElree (2007) find increased activation of vmPFC for coercing sentences. Schumacher (2013) reports late positivities for container-for-content metonymies (e.g., "The baby drank the bottle"). Paczynski et al. (2014) demonstrate that aspectual coercion (i.e., composition of punctual verbs and durative adverbs, e.g., "For several minutes, the cat pounced on the toy") is indexed by a late anterior negative ERP. In these studies, the conditions are closely matched, but precritical material is not kept constant. The focus on semantic differences between conditions, motivated by theory, is a valid way forward to investigate the online processing of these constructions and has the potential to refine linguistic theories. Still, the variable results emerging from these studies point to effects specific to the different linguistic phenomena investigated by each study as opposed to a neural correlate unique to composition.

Other studies are designed around syntactic or semantic properties of languages. Flick and Pylkkänen (2020) use properties of English in an attempt to vary syntax while keeping meaning constant. In English, attributive adjectives occur canonically before a noun, but they may also occur post-nominally in specific constructions. They compared declarative sentences with post-nominal modifiers ("There are many trails wide enough for a bear") to questions with post-nominal predicative adjectives ("Are many trails wide?"). A novel aspect here, which is not found in minimal phrases, and to which we return later, is that the critical and pre-critical words form *identical sequences across conditions* ("... trails wide ..."). The authors find an effect of structure in the left posterior temporal lobe (PTL) around 200 ms after the onset of the adjective, and an effect of semantic fit between the adjective and noun in the LATL.

Parrish and Pylkkänen (2022) use semantic and syntactic properties of English to vary the point of composition. They compare expressions where an adverb and an adjective enter into local composition (e.g., "pleasantly sunny days") to expressions where two adjectives compose with a noun, but not locally with each other (e.g., "pleasant sunny days"). In this study, the precritical word was matched across conditions at the lemma or concept level, but not in its grammatical form. A further comparison involved structures such as "this herbal tea", where "tea" and "herbal" readily combine with each other, to conditions where they do not because of a gender mismatch: "these herbal tea ...". In this case, participants must wait until they see a noun that closes the phrase, like "these herbal tea drinkers". A non-combinatorial condition was created by placing the critical word at the start of the sentence, where it has no previous material to combine with: "Tea drinkers hate coffee". Composition in LATL can proceed in the absence of syntactic phrase closure, but syntax can also influence activity in this region, with the highest activity seen for phrases that were both syntactically and conceptually straightforwardly composable.

Matchin et al. (2019b) exploit the fact English participle adjectives and past tensed verbs have the same form to construct modification and predication pairs (e.g., "the frightened boy" vs. "frightened the boy"), plus a list baseline (e.g., "frightened, scrubbed, wounded"). They found no differences in BOLD responses in the left ATL and AG. The left posterior STS and LIFG showed greater activity for predication (VP) vs. modification (NP). Matar et al. (2021) use unique properties of the Arabic language to achieve minimally differing stimuli where only syntactic composition varies. In Arabic, an adjective follows the noun it modifies. If the adjective and noun carry the definiteness marker (e.g., "al", in "al-kursi al-banafsaji", the purple chair) the result is an NP; if only the noun does (e.g., "al-kursi banafsaji", the chair is purple), a full sentence results. These two conditions were further compared to an indefinite NP (e.g., "kursi banafsaji", a purple chair). There were no MEG effects of syntactic structure in the left IFG, ATL, and AG. The left posterior temporal lobe (LPTL) was engaged more for indefinite NPs than for definite NPs, and least of all for sentences. The direction of this effect (NP > S) is opposite to that reported by Matchin et al. (2019b) (VP > NP) in the same region of the left posterior temporal cortex. Using a similar approach, Artoni et al. (2020) used Italian sentences containing noun phrases or verb phrases containing homophone two-word sequences, e.g., "la porta" in (13), which is either a Det-N phrase (13a) or a clitic followed by a verb in (13b) (the fragment "domani la porta" is in fact structurally ambiguous: Adv-VP vs. Adv-NP):

(13) a. Pulisce **la porta** con l'acqua.
[He/she] washes ***the door*** *with water.*
b. Domani **la porta** a casa.
[He/she] tomorrow ***takes her/it*** *at home.*

Using direct cortical EEG recordings, they found increased gamma activity above 150 Hz for VPs compared to NPs in large portions of the left hemisphere, beyond the LIFG and posterior STG/STS. The studies presented in this section compare conditions where the degree or type of composition varies to identify correlates responsible for the difference. However, to isolate composition true non-combinatorial conditions that do not have the limitations discussed so far would be needed.

3.2. Frequency tagging paradigms

Another approach to the study of structure building and indirectly meaning composition is the frequency tagging (or neural tracking) paradigm. By using rhythmically presented stimuli, recent studies have shown that neural oscillations in particular frequency bands can align with chunks at different levels of syntactic structure, as shown by peaks in the power spectrum of particular frequency bands (Ding et al., 2016) or increases in mutual information (MI) between auditory stimuli and neural oscillations (Kaufeld et al., 2020).

Ding et al. (2016) and Sheng et al. (2019) compared scrambled syllable sequences with 4-syllable sentences and 4-syllable NPs and VPs, matched in length but differing in the point at which structural dependencies are formed. They found rhythmic brain activity tracking each level of structure: syllable, phrase, sentence. There were no prosodic cues or breaks between sentences in a sequence: those effects can be attributed to synchrony of neural activity to internally generated structures (Meyer et al., 2020; see Kazanina and Tavano, 2023 for discussion). While Sheng et al. (2019) use MEG, Ding et al. (2016) also present ECoG data. They found activity modulated at the phrase frequency in bilateral pSTG, and in the left IFG and pSTG at the sentence frequency.

Coopmans et al. (2022) compared normal sentences (14a) to idiomatic sentences (14b), anomalous prose (14c), Jabberwocky (14d), and scrambled sentences (14e):

(14) a. De jongen gaat zijn zusje met haar huiswerk helpen.
The boy will help his sister with her homework.
b. De directie zal een vinger aan de pols houden.
The directorate will keep a finger on the wrist.
c. Een prestatie zal het concept naar de mouwen leiden.
An achievement will lead the concept to the sleeves.
d. De jormen gaat zijn lumse met haar luisberk malpen.
The jormen will malp his lumse with her luisberk.
c. De gaat jongen zusje huiswerk zijn haar helpen met
The will boy sister homework his her help with

This study shows how a combination of different baseline conditions and advanced data analysis techniques allows us to track neural dynamics across conditions. At the phrase frequency, there were no differences in MI between sentences and anomalous prose, or sentences and idioms, but they found increased neural tracking in sentences compared to lists and Jabberwocky, as in Kaufeld et al. (2020). ERPs show differences between all of these conditions, but neural tracking reveals similarities across conditions containing structure and content words, pointing to a common mechanism for composition.

Burroughs et al. (2021) adapt the paradigm used by Ding et al., in an experiment aimed at disentangling the effects of word category repetition from those of structure building. They found that the neural signal tracks syntactic structure, with increased tracking in the delta band for lists of phrases ("cold food loud room tall girl") vs. lists of words with repetitions of syntactic categories without structure ("rough give ill tell thin chew"). This effect is however modulated by syntactic category, with reduced tracking when the list of phrases did not contain repetition of syntactic categories ("that word send less too loud"). These results suggest that previous studies using the frequency tagging paradigm may have also included spurious effects of syntactic category repetition.

Glushko et al. (2022) use EEG to disentangle the effects of syntax from those of prosody. They used sentences containing four words of the form NP-VP, with the NP consisting of 1 word (1+3 Syntax) or 2 words (2+2 Syntax) without prosody. These were then compared to trials containing the same syntactic structures but with a prosodic contour compatible with the 2+2 Syntax condition. Their results show an interaction between prosody and syntactic structure, suggesting that the generation of implicit prosody affects syntactic composition and that previously reported effects using the neural tracking paradigm can be partially explained by prosody effects.

Kalenkovich et al. (2022) used Russian sentences containing the same number of words and lexical content and differing only by the use of a single suffix, which affords them a different syntactic structure. They created sentences with words grouped into 2 phrases (Genitive 2-2) and sentences containing a noun in the dative case with the same words grouped in a 1 word NP and a 3 word verb phrase (Dative 1-3). Interestingly, the spectral peaks between conditions at the 2-word frequency did not differ, suggesting that factors like repetition of lexical category might explain previous effects.

The frequency tagging paradigm has become popular since its introduction by Ding and colleagues. The conclusions originally drawn from those experiments have been recently challenged on empirical and theoretical grounds (Kazanina and Tavano, 2023), suggesting that the rhythmicity of stimulus presentation may introduce processes that stand in the way of observing neural correlates of structure building.

3.3. The cut-compose paradigm

The studies reviewed in Sections 1–2 investigate composition by comparing well-formed language to baselines that are assumed not to engage composition. It is unclear to what extent pseudowords and word lists prevent composition: composition-related signal can be lost if both conditions under comparison engage composition. A second challenge is that those baselines can differ from compositional expressions on several levels besides composition, leaving in mixed signals after subtraction or comparison. A third difficulty is that pseudoword sentences, word lists, and phrases are not as natural and informative as full sentences and can require additional pragmatic support, when they do not violate pragmatic constraints altogether.

We describe a novel paradigm for studying composition which tries to take into account the three limitations of previous paradigms: lack of minimality, lack of naturalness, and unsuccessful prevention of composition. The goal here is to learn from the successes and failures of previous studies and to explore possible new avenues in experimental design.

The Cut-Compose paradigm makes use of natural, well-formed, and complete sentences, varying the presence or absence of composition at specific points in the input string. The idea is to force or prevent composition in well-formed, meaningful sentences or pairs of sentences by exploiting syntactic boundaries:

(15) a. Some birds sit on [***grey elephants***] and clean them.
b. Some birds are completely [***grey***.][***Elephants***] can be white.

The same sequence of two words can occur as part of the same constituent, in (15a), the Compose condition, or as separated by a syntactic boundary, in (15b), the Cut condition, in this case also marked by punctuation. The first EEG study using this design, by Olstad et al. (2020), removed punctuation marks in order to match the precritical (e.g., "grey") and critical ("elephants") words. Additional safeguards had to be implemented to prevent accidental composition in the Cut condition. First, syntactically, the adjective "grey" has a predicative role, so it cannot modify "elephants".

Second, semantically, "Some birds are completely grey elephants" would be anomalous. Third, the critical word initiates a new sentence, rather than a new phrase in the same sentence; this should block composition of larger constituents (e.g., phrases or clauses) higher up in the syntactic structure. One challenge is to match the precritical context in length, grammatical complexity (e.g., in syntactic nodes or arcs) and semantic associations: this is crucial for experiments using hemodynamic methods, while M/EEG studies should also attempt to control the factors that affect composition locally, around the boundary. The difference between Compose and Cut is meant to reveal that which differs between the two conditions, namely the composition of the adjective "grey" with the noun "elephants" in (15a) but not (15b).

Similar to other paradigms, Cut-Compose also affords the possibility of investigating the compositional mechanisms involved in different semantic and syntactic contexts. Olstad et al. (2020) compared modification as in (15), with predication constructions as in (16), to assess whether these two different "modes of composition"—Predicate Modification vs. Functional Application, Adjoin vs. Merge—correspond to different neural events. As the study was conducted in Norwegian, the Cut sentence was created by fronting the object:

(16) a. bråk er slitsomt men noen [**hører musikk**] blant alle lydene
noise is tiring but some [*hear music*] *among all the sounds*
b. bråk er innimellom noe man **hører musikk** er flott
noise is sometimes something one hears music is nice

In (16a), the proposition is incomplete without "musikk", as the verb "hører" requires two arguments to be saturated. This contrasts with Cut (16b), where the verb argument slots are all filled by "hører", leaving no room for "musikk" to compose with the verb. Different modes of composition can be directly compared in the same experiment, as the noun at which the M/EEG signal is measured can be held constant across environments. The sentences in (17) are examples of stimuli in the modification condition Olstad et al. (2020):

(17) a. på byggeplasser spilles [bråkete musikk] på radioen
on construction sites is played [*noisy music*] *on the radio*
b. byggeplasser er bråkete][musikk kan være avslappende.
construction sites are noisy][*music can be relaxing*

Olstad et al. (2020) found different ERP signals for the different modes of composition, providing support for the theoretical distinction between predication and modification, as well as preliminary evidence for the viability of the Cut-Compose paradigm.

Does composition not happen at all in the Cut condition? In both conditions, the critical noun is eventually composed into a higher-order representation: it is combined with the previous words in Compose, while it is yet to be combined with subsequent material in Cut. However, in the Cut condition, composition does not occur *between the noun and its preceding context*, and this the key difference with Compose. In contrast to artificial stimuli such as nonword or pseudoword strings, in Cut/Compose participants should be equally engaged in reading both types of sentences, implying a more equal distribution of cognitive resources (attention, memory etc.) across conditions. Additionally, both Cut and Compose are covered by theory: all formal linguistic theories on the market predict that composition is triggered in one case but not the other, at the point of measurement.

As other paradigms, Cut/Compose has limitations related to the baseline condition. One potential issue is the use of punctuation, which is necessary in order to make the stimuli as natural and as unambiguous as possible. Adding a period after the precritical word in Cut sentences creates a perceptual difference between the two conditions. An additional perceptual difference is capitalization of the first letter of the critical word in Cut. Olstad et al. (2020) avoided the use of punctuation and capitalization, relying on the structural properties of sentences to ensure that the noun is interpreted as starting a new sentence in the Cut condition. Follow-up experiments are needed to investigate the effects of both punctuation and capitalization in the visual modality, whether they affect the detection and quantification of composition signals, and the corresponding impact of appropriate prosody or intonation around the Cut boundary in the auditory modality.

Another possible issue is that critical nouns in the Cut condition introduce a new phrase and sentence, and may therefore engage different processes than nouns in the Compose condition which *close* a phrase or sentence. This issue may be partly addressed in future experiments where the syntactic cut is not a sentential boundary but a phrasal one. Note that inferences drawn regarding different modes of composition should still be valid, as opening a new sentence in the Cut condition should involve the same processes for both predication and modification contrasts. A different issue is that of discourse processing. The second sentence in the Cut condition is not disconnected from the first one. At the critical noun, the participant might try to integrate it into the discourse model instead of waiting to read the rest of the second sentence. However, integration with the preceding context also happens in Compose sentences, though the discourse representation in that case is not organized into multiple sentential or propositional units.

Similar to constituent chunking studies, like Pallier et al. (2011), Cut/Compose relies on manipulating the number of syntactic units between conditions, while it tries to control more precisely the immediate context of the critical word as well as aspects of the wider semantic context. Cut-Compose can be used with a variety of constructions, differing in semantic or syntactic properties, complexity and length. Many questions that have been of interest for other paradigms can also be tested with Cut/Compose: coercion, different classes of adjectives, adverbs, nouns and verbs, as well as the composition of functional and lexical elements. In the long run, we will be able to inch closer to the mechanisms by which the brain builds structure and meaning only by integrating results from different paradigms, different measures and data analysis methods. Cut/Compose aims to make a contribution to this longer-term project, and might also prompt the development of new and improved paradigms beyond the currently available ones.

TABLE 2 Summary of designs and results from a selection experiments on syntactic structure building and semantic composition grouped according to the paradigm used.

Paradigm	References	Results	Task	Acquisition method	Stimuli presentation
Normal sentence vs. scrambled sentence	Kaufeld et al., 2020	Increased neural tracking at phrase frequency in sentences vs. scrambled sentences	No task	EEG block design	Auditory
	Vandenberghe et al., 2002	Left anterior temporal pole, left anterior STS, left posterior temporal gyrus	Press a button if two stimuli followed each other	PET block design	Visual
	Humphries et al., 2006	Left anterior STS, left inferior temporal gyrus, left AG, left ATL	Rate stimuli for meaningfulness	fMRI event-related design	Auditory
	Hultén et al., 2019	Left PTC, left IFC, left ATL 400 ms after word onset	Yes/no question (20% of trials), word probe task for lists, comprehension question for sentences	MEG block design	Visual
	Mollica et al., 2020	Left IFG, left ATL, left PTL, left MFG, left AG for intact or moderately scrambled items vs. fully scrambled items	Word probe task after each trial	fMRI event-related design	Visual
	Nelson et al., 2017	High-gamma power increases at each new word, decreases when a word completes a phrase: left temporal, inferior frontal cortex	Sentences probe task in sentence trials, word probe task in lists trials (75% of trials)	ECoG event-related design	Visual
Normal sentence vs. anomalous or incongruent sentence	Vandenberghe et al., 2002	No effect; effect of anomalous vs. normal sentence in left MTG	Press a button if two stimuli followed each other	PET block design	Visual
	Humphries et al., 2006	Left AG, ITS, ITG, anterior STS	Rate each stimulus for meaningfulness	fMRI event-related design	Auditory
Normal sentence vs. word lists (without function words)	Friederici et al., 2000	Left posterior STG, planum polare bilaterally	Indicate whether a target word or syntactic structure was present in the previous trial	fMRI event-related design	Auditory
	Branco et al., 2020	Left IFG; left TP, MTG, SMG; left SFG, MFG; right STG; right TP	Word probe task: select which of two words was present in the previous trial	fMRI block design	Visual
	Law and Pylkkänen, 2021	Left IFG (250–300 ms), left ATL (300–350 ms), left PTC (330–400 ms)	Word probe task	MEG event-related design	Visual
	Zaccarella et al., 2017	Left IFG, left posterior STS	Decide whether the previous trial was a phrase/sentence or word list	fMRI block design	Visual
Normal sentence vs. word lists (with function words)	Humphries et al., 2005	Left posterior STS, left anterior STS/MTG	No task	fMRI event-related design	Auditory
	Fedorenko et al., 2016	Gamma increase in left frontal, left lateral temporal, left ventral temporal cortex	Word probe task	ECoG event-related design	Visual
	Matchin et al., 2017	Left IFG, STS, ATL	Word probe task	fMRI block design	Visual
	Pallier et al., 2011	Increased activity with constituent size in left IFG, TP, TPJ, STS	Rare probe sentence asking to press a button on the basis of previous trial and a word memory test at the end of each run.	fMRI event-related design	Visual

(Continued)

TABLE 2 (Continued)

Paradigm	References	Results	Task	Acquisition method	Stimuli presentation
Constituent chunking: sentence vs. phrase	Shain et al., 2021	Left IFG, MFG, ATL, PTL, AG	No task?	fMRI event-related design	Visual
	Matchin et al., 2017	Left IFG, posterior STS, ATL	Word probe task	fMRI block design	Visual
	Matchin et al., 2019a	Left ATL, left PTL (subject NP), left TPJ (object NP)	Word probe task	MEG block design	Visual
Normal sentence vs. pseudoword- or nonword-sentence	Friederici et al., 2000	No effect	Indicate whether a target word or syntactic structure was present in the previous trial	fMRI event-related design	Auditory
	Branco et al., 2020	No effect	Word probe task: select which of two words was present in the previous trial	fMRI block design	Visual
	Fedorenko et al., 2016	Gamma increase in left frontal, left lateral temporal, left ventral temporal cortex	Word probe task	ECoG event-related design	Visual
	Humphries et al., 2006	Anterior, middle, posterior STS, MTG, left ITG, bilateral AG	Rate each stimulus for meaningfulness	fMRI event-related design	Auditory
	Stromswold et al., 1996	Left IFG, left STS; left SMG gyrus (for reverse contrast)	Judge the goodness of each sentence	PET block design	visual
	Segaert et al., 2018	Alpha and beta power increases after presentation of first word; alpha power increases after presentation of second word immediately after word onset	Detect reversed speech segments	EEG event-related design	Auditory
	Iwabuchi and Makuuchi, 2021	Left ATL, ventral occipital cortex (placeholders instead of pseudowords)	Judge whether the content of a probe sentence matched the content of the previous trial (task after 60% trials)	fMRI event-related design	Visual
	Kaufeld et al., 2020	Increased neural tracking at phrase frequency	No task	EEG block design	Auditory
	Matchin et al., 2017	Left IFG, left ATL, left PTL (whole brain analysis)	Word probe task	fMRI block design	Visual
	Matchin et al., 2019b	Left IFG, left ATL, left PTL, left TPJ (all at 215–350 ms after open class word onset)	Word probe task	fMRI block design	Visual
	Pallier et al., 2011	Left TP, TPJ, anterior STS	Probe sentence, press a button on the basis of previous trial; word memory test at the end of each run	fMRI event-related design	Visual
	Shain et al., 2021	Left IFG, left MFG, left ATL, left PTL, left AG	No task?	fMRI event-related design	Visual

(Continued)

TABLE 2 (Continued)

Paradigm	References	Results	Task	Acquisition method	Stimuli presentation
Minimal phrases	Bemis and Pylkkänen, 2011 Adj-N vs. nonW-N	Increased activity in left ATL (84–225 ms) and vmPFC (300–500 ms)	Participants saw colored images in *composition* task and a colored blob and an outline in *non-composition* task: decide whether all words in the previous trial match the image	MEG block design	Visual
	Bemis and Pylkkänen, 2013a Adj-N vs. NonW-N	Left ATL (200–250 ms) regardless of word order in the compose task and for canonical word order in the non-compose task	Participants saw colored images in *composition* task and a colored blob and an outline in *non-composition* task: decide whether all words in the previous trial match the image	MEG between-subjects block design	Visual
	Bemis and Pylkkänen, 2013b Adj-N vs. nonW-N	Left ATL (191–299 ms visual modality; 268–323 ms auditory); left AG (336–390 ms in visual modality, 537–591 ms in auditory modality)	Participants saw colored images in *composition* task and a colored blob and an outline in *non-composition* task: decide whether all words in the previous trial match the image	MEG block design	Visual and auditory
	Fló et al., 2020 Experiment 1:Adj-N vs. nonW-noun	Negativities at 260–55 ms and 410–600 ms after word onset	Participants saw colored images after each trial; *composition* task: decide whether both words in previous trial match the image; *non-composition* task: decide if any of the preceding words match the image	EEG block design	Visual
	Fló et al., 2020 Experiment 2:Adj-N vs. nonW-noun	No effect of composition	Decide whether the image after each trial matches the preceding material	EEG event-related design	Visual
	Fritz and Baggio, 2020, 2022 Adj-N vs. nonW-N and pseudoW-N	450–700 ms positivity over centro-parietal channels (P600 ERP)	Comprehension questions after each trial	EEG event-related design	Visual
	Kochari et al., 2021 Adj-N vs. nonW-N	No effect	One or two words followed by a question mark; participants had to convert them into questions and answer	MEG event-related design	Visual
	Neufeld et al., 2016 Adj-N vs. nonW/pseudoW-N	Anterior negativity—50–100 ms starting at the first word; centro-parietal negativity after onset of second word (180–400 ms)	Participants saw colored images after each trial; *composition* task: decide whether both words in the previous trial match the image; *non-composition* task: decide if any of the preceding words matches the image	EEG block design	Visual
	Graessner et al., 2021b Adj-N vs. Adj-pseudoW	Task independent: left posterior AG, left posterior ITG; dorsomedial PFC. Explicit task: left anterior IFG, left ATL, left posterior MTG, left posterior AG, dorsomedial PFC, cerebellum. Implicit task: left AG, left posterior MTG/ITG, dorsomedial PFC	Session 1: implicit task: indicate whether both words had the same or different lexical status. Session 2: explicit task: indicate whether the phrase is meaningful or not	fMRI event-related design	Auditory

(Continued)

TABLE 2 (Continued)

Paradigm	References	Results	Task	Acquisition method	Stimuli presentation
	Murphy et al., 2022 Adj-N vs. pseudoW-N vs. adj-pseudoW	Broadband gamma activity 210 ms after noun onset in portions of posterior STS	Participants saw colored pictures after each trial: decide whether the picture fully matches the previous phrase	iEEG/ECoG event-related design	Auditory
	Kim and Pylkkänen, 2019 Adverb-verb vs. nonW-verb	Increased activity at 250 ms in left ATL for eventive adverbs, in right ATL for agentive adverbs	Participants chose among two nouns which one fit best the meaning of the previous phrase	MEG event-related design	Visual
	Boylan et al., 2015 V-N/P-N/V-adv/adj-N vs. N/V-nonW	Activation in left and right AG for phrases sharing a verb regardless of composition type	Press a button indicating whether a two-word phrase was synonymous with the previous trial (30% of trials)	fMRI event-related design	Visual
	Zaccarella et al., 2017 PP-Det-N vs. 3-word list	Left IFG (BA44), left pSTS	Categorize the type of the previous trial (sentence, phrase word list, "rubbish")	fMRI block design	visual
	Matchin et al., 2019b V-Det-N vs. Det-A-N vs. lists of 3 words	Composition: left AG, left ATL, left posterior STS, left anterior IFG VP > NP: left posterior IFG, left posterior STS	Phrase probe task. After sequences of 3 trials participants saw a probe similar to a previous trial with one word changed; decide whether the probe is synonymous with one of the preceding trials	fMRI block design	Visual
	Westerlund et al., 2015 Modification: adj-N vs. nonW-N; adv-V vs. nonW-V; adv-adj vs. nonW-ADJ Argument saturation: V-N vs. nonW-N; P-N vs. nonW-N; det-N vs. nonW-N	Left ATL activation around 250 ms after second word onset for both composition types, but earlier for saturation	Phrase probe task after 20% of trials; indicate whether the probe is related to the previous trial	MEG event-related design	Visual
	Strijkers et al., 2019 PersPron-V/PossPron-N vs. ###-N/V	Activity in left and right IFG (starting 80 ms after second word) for N vs. V in combinatorial conditions only	Detect catch phrases (second word is a pseudoW)	MEG event-related design	Visual
	Kim and Pylkkänen, 2021 N-V-N vs. ###-V-N vs. ###-###-N	Subject-verb composition: left ATL (313–376 ms), left middle STC (332–364 ms); no effect for verb-object composition	Decide whether a picture presented after each trial accurately describes the linguistic material in the previous trial	MEG event-related design	Visual
	Lau and Liao, 2018 Adj-N and adj-N vs. adj-N ### adj-N	Increased anterior negativity starting at the first word of the second phrase lasting throughout the epoch	Memory probe of two words (20% of trials)	EEG block design (Experiment 1); event-related design (Experiment 2)	Visual
	Schell et al., 2017 A-N vs. N; Det-N vs. N	Adj-N composition: left IFG (BA45), left AG; det-N composition: left IFG (BA44), left posterior STS	Decide whether the previous trial could be integrated in a normal sentence	fMRI event-related design	Auditory

The paradigms included are those reviewed in Section 2. We report the results for the comparisons between well-formed meaningful sentences or phrases and the relevant baselines (specified in columns 1 or 2).

4. Weighing the options: What are we left with?

We have reviewed studies using different paradigms that tried to isolate composition in brain signals. The limitations of the paradigms discussed here are not entirely unknown and have been occasionally pointed out before (e.g., see Humphries et al., 2006; Matchin et al., 2017, 2019a). In this section, we reflect on what has been achieved so far in mapping semantic composition in brain space and time (for an earlier assessment, see Baggio, 2018). Table 1 summarizes our evaluation of the paradigms discussed above, and Table 2 is an overview of the main results of different studies. Our recommendation for the field includes developing new paradigms that overcome the limitations of current ones. A parallel strategy is to integrate results *across* studies and paradigms, in the hope that paradigms with complementary strengths and limitations would support each other and allow more reliable inferences from data. We briefly pursue this avenue here.

Despite their limitations, the words list and scrambled sentence paradigms allow lexical variables between stimuli to be matched. Although comparing sentences with scrambled versions may result in loss of signal (see above), scrambled sentences should still involve "less composition". Results from studies using this paradigm could help narrow down the search space of correlates of composition: regions engaged across studies using different baselines are candidate correlates of composition; regions that differ across studies may be related to processing of the particular stimuli used. The left posterior STS/STG, ATL, and AG consistently show up in normal vs. scrambled sentences contrasts. The left IFG is active in studies with difficult or engaging tasks, in studies using lists without function words, or words not in the original sentences. Further research is needed to understand how different baselines affect comparisons with normal sentences.

Jabberwocky sentences are a clever way of disentangling syntax from semantics, though formal aspects of meaning remain in stimuli with real function words and affixes. In this sense, like lists of words, Jabberwocky may involve semantic composition, but to a lower degree. Studies using this design often either reveal regions that overlap with those from studies using word lists or no effects in comparisons to sentences. Negative findings may suggest that lists are a better baseline than Jabberwocky, while overlapping results may indicate either that they are both equally effective or that both have issues with the same impact on brain signals. Minimal phrase designs using real word lists or pseudowords in baseline conditions have arguably made the most progress in narrowing down the space of correlates of composition. Zaccarella et al. (2017) and Matchin et al. (2017) implicate left IFG and pSTS in composition, while Murphy et al. (2022) localize effects of phrasal composition in pSTS around 200–300 ms from word onset. Inconsistencies remain across studies using minimal phrases as to the regions involved (left IFG, AG, vmPFC), with one frequently reported region being the left ATL. Yet, the LATL is mostly sensitive to *conceptual composition*. Integrating results from the studies in Table 2 we thus find a network in the left perisylvian cortex, with possibly the most functionally critical node in the posterior superior temporal gyrus and sulcus.

Section 3 considers alternative strategies, including testing theoretical distinctions Section 3.1, using advanced analysis methods Section 3.2, and developing new paradigms Section 3.3. We believe that initiating a discussion on the need to refine our paradigms is a crucial step forward, but a combination of approaches, as suggested in Section 3, as well as comparing results across methods (Table 2), is already leading to testable new hypotheses about the likely cortical seats and time course of syntax-driven meaning composition.

Our assessment of the different paradigms in Table 1 suggests that they are not all equal in their strengths and limitations. But the important lesson here is that while paradigms can be assessed on design grounds alone, they must also be evaluated *empirically* based on the plausibility and consistency of the results they generate: it is impossible to know exactly how the brain reacts to the different conditions a priori, and thus how severe the issues identified a priori may actually be. Comparing results across different paradigms can not only help us restrict the search of correlates of composition to fewer candidates: it can also provide indirect evidence of the actual impact of the limitations of particular paradigms. That said, this complex evaluative exercise remains fraught with difficulties, and is ultimately based on researcher choices, expertise, and judgement. For this reason, the way forward for the field should also involve the development of new paradigms and cannot be based entirely on comparison and integration of results across existing ones.

5. Conclusion

This review has examined experimental paradigms and designs used to search for neural correlates of syntax-driven meaning composition. Our aim was to dissect each paradigm presenting the ways in which it has been implemented in specific studies, bringing forth its goals and assumptions, and uncovering its strengths and weaknesses. One conclusion concerns the lack of baseline or control conditions that can fully prevent composition at specific points in time. Without such conditions, interpreting comparisons with phrases or sentences remains difficult: any claim that a given signal is a correlate of composition is undermined, if the conditions compared do not *only* differ in whether composition is engaged or not. This may partly explain why M/EEG or fMRI studies have not revealed correlates of composition invariant across studies or paradigms (Table 2). But as noted, the challenge ultimately involves more than just experimental design: finding the neural mechanisms of composition will also require progress in integrative theory (van Rooij and Baggio, 2020, 2021), recording resolution, and data acquisition and analysis.

Here, we have focused on a neglected, yet essential ingredient of research methodology: the internal validity of experimental paradigms and designs. Our critique is not meant to devalue the ingenuity of experimental designs used by researchers throughout the years: we have contributed to this research ourselves, and we have used several of the classical paradigms in our work. Some of the issues raised here were also noted by others, but we believe it is useful to assess different paradigms comparatively and systematically, using the same standards. In addition to examining the limitations of baseline conditions, we should reconsider the theoretical assumptions about composition that we build into our experimental designs. The brain may not always automatically compute meaning taking syntactic structure into account: if syntax is not always deployed during comprehension, or if lexical processing in well-formed and meaningful sentences always engages a set of independent operations in addition to syntax-driven composition, then any comparison of conditions, even assuming adequate baselines, will reveal either less or more in terms of neural signals than syntax-driven composition (Baggio, 2018, 2022).

Consider the "standard view" of meaning composition from generative syntax and formal semantics. As a computational implementation of composition, that view may not quite provide what psycholinguists and neurolinguists need to derive specific predictions and explain existing experimental results. One reason is that there is still no real consensus on the atoms and structures of syntax in the first place, their relation to lexical encoding, and the semantic primitives of combination they correspond to. The logical calculus of formal semantics works equally well for very different choices of syntactic and semantic ontology: the existence of a syntax-semantics interface that respects function-argument composition does not, in and of itself, provide a unique answer to what those syntactic and semantic primitives are. Moreover, there are indications that the basic combinatoric building blocks assumed in formal semantic theory do not map in any systematic way to basic differences and measures at the neurolinguistic level (Pylkkänen and McElree, 2006).

Putting aside open questions of what the minimal parts and modes of combination are, one could disagree with the particulars of this narrow formulation, and specifically with the centrality of Compositionality (Baggio et al., 2012b; Baggio, 2018, 2021). But the key insight here is that human languages have algorithms for building meanings predictably from their parts. Predictability and generativity of meaning should be taken seriously as computational constraints modulating language processing and its outputs, even though not all complex meanings may be equally subject to Compositionality. Developing better experimental paradigms should go hand in hand with theoretical and modeling efforts aimed at charting the different ways in which brains actually build meaning.

Author contributions

LC did the literature search and selected the relevant studies. LC, GB, and GR wrote and edited the paper. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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False perspectives on human language: Why statistics needs linguistics

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A sharp tension exists about the nature of human language between two opposite parties: those who believe that statistical surface distributions, in particular using measures like surprisal, provide a better understanding of language processing, vs. those who believe that discrete hierarchical structures implementing linguistic information such as syntactic ones are a better tool. In this paper, we show that this dichotomy is a false one. Relying on the fact that statistical measures can be defined on the basis of either structural or non-structural models, we provide empirical evidence that only models of surprisal that reflect syntactic structure are able to account for language regularities.

One-sentence summary: Language processing does not only rely on some statistical surface distributions, but it needs to be integrated with syntactic information.

KEYWORDS

syntax, surprisal, linguistics, POS, syntactic surprisal

A sharp tension exists about the nature of human language between two opposite parties: those who believe that statistical surface distributions, in particular characterized using measure like surprisal, provide a better understanding of language processing, vs. those who believe that discrete recursive hierarchical structures implementing linguistic information are a better tool, more specifically, syntactic structures, the core and unique characteristic of human language (Friederici, 2017). In this paper, we show that this dichotomy is a false one. Relying on the fact that statistical measures can be defined on the basis of either structural or non-structural models, we provide empirical evidence that only models of surprisal that reflect syntactic structure are able to account for language regularities. More specifically, our goal is to show that the only kind of surprisal measure that is well correlated with behavioral or brain measures is one which takes into account syntactic structure. We do so by showing that the syntactic surprisal is the only surprisal measure able to distinguish our stimuli in the same way a human listener would do. Crucially, here all confounding factors, including acoustic information, will be factored out distinguishing our study from previous in the field, such as in Frank et al. (2015), Brennan and Hale (2019), Shain et al. (2020).

1. On four different models of surprisal

It is a truism that during language processing the brain computes expectations about what material is likely to arise in a given context. The natural next step from this observation and one that characterizes much work in psycholinguistics is to formulate a hypothesis about the differences in processing load: in general, the less expected a piece of linguistic material is, the more difficult its processing (Taylor, 1953; Goldman-Eisler, 1958). Expectation can be quantified in terms of the information theoretic notion of Surprisal (Attneave, 1959), where the surprisal of a word w in context w_c is defined as:

$$Surprisal\,(w|w_c) = -\log p\,(w|w_c) \qquad (1)$$

If a word is highly unlikely in a context, its surprisal will be very high. In contrast, if the word's is highly likely, its surprisal will approach 0.

Surprisal serves as a very useful linking hypothesis between patterns of behavior and brain response on the one hand and a single numerical quantity, namely the probability of a form. And because surprisal does not make explicit reference to linguistic structure, surprisal is often thought to provide an alternative perspective on language processing that avoids the necessity to posit such structure. This view is incorrect, however. Surprisal depends crucially on a particular characterization of a word's probability. Such a characterization, a probability model, may or may not make reference to linguistic structure. In this section, we will describe two dimensions along which language probability models can vary, and then use these dimensions to characterize four distinct probability models. Each of these models can be used as the input to the surprisal equation given above, so that different values of surprisal can result depending on the assumptions behind the probability model (see Figure 1).

1.1. Dimension 1: sequences vs. hierarchical structure

Our first dimension concerns the structure that is assumed in the generation of language. The simplest conception views language as a concatenative system. In this view, a sentence is simply a sequence of words generated one after another in a linear fashion. To account for which sentences are well-formed and which are not, constraints are imposed on adjacent elements, or bigrams. For example, in the context preceded by word "the", a linear model of English will permit words like "cat" or "magazine" to occur, but not "of". To make a probability language model, we can simply assign a probability to a word w in a given context defined by the previous word w_c, so that the probabilities for all of the words sum to 1 for each context. Given a sufficiently large corpus, we can estimate these probabilities by taking the ratio of the number of occurrences of the context and of the context-word bigram:

$$p\,(w|w_c) = \frac{count\,(w_c,\ w)}{count\,(w_c)} \qquad (2)$$

This model can be extended to an n-gram model, where the length of the context is increased to include more material: in an n-gram model, the conditioning context will include n-1 words. A 3-gram model could thus assign a higher probability to "magazine" than "cat" in the context "read the" while doing the reverse in the context "fed the". A bigram model could not assign distinct probabilities in the two contexts, since the single adjacent word, namely "the", is identical in both. For this reason, an n-gram model gives a more refined assessment of likelihood as the value of n grows. However, because the number of conditioning contexts expands exponentially with the length of the context, it becomes increasingly difficult to accurately estimate the values of the probability model. A variety of methods have been proposed to integrate the information from longer contexts with information in shorter contexts. We use such a composite model for our model of **N-gram surprisal**.

Chomsky (1957) famously argued that linear models, were inadequate models of natural language, as they are incapable of capturing unbounded dependencies. To illustrate, consider the likelihood of the word "is" or "are" in context "The book/books that I was telling you about last week during our visit to the zoo". This will depend on the whether the word "book" or "books" appears in the context. Because the distance between this contextual word and the predicted verb can grow without bound, no specific value of n will yield an n-gram model that can correctly assign probability in such cases.

Chomsky's suggested alternative generates language using a hierarchically organized process. In this way, linearly distant elements can be structural close. One simple model for this involves context-free grammars (CFG), a set of rules that specify how a unit in a sentence tree can be expanded:

S → NP VP
NP → Det N
VP → V NP | V
Det → the | a
N → book | books
V → read | reads

Where S is the sentence, NP is a noun phrase, VP is a verb phrase, Det is a determiner, N is a noun and V is a verb.

Generating a sentence with such a grammar starts at the start symbol S. A rule whose lefthand side matches this symbol is then selected to expand the symbol. Each element of this expansion is in turn expanded with an appropriately matching rule, until the only remaining unexpanded symbols are words. The result of this CFG derivation is a tree-structured object T, whose periphery consists of the words of the sentence that is generated, called the yield of T. A CFG can be used as the basis of a probability model by assigning probability distributions for the possible expansions of each symbol (i.e., a value between 0 and 1 is assigned to each rule, with the values for the rules that share the same lefthand side summing to 1). In such a probabilistic CFG (PCFG), derivations proceed as with CFGs, but the choice of expansions is determined by the probabilities. In PCFGs, the probability of a tree structure is the product of the probabilities of each of the expansions. Because a sequence of words S might be generated by different trees, the probability of S is the sum of the probabilities of all of the trees T with yield S. Hale (2001) shows how to use PCFGs to calculate the surprisal for a word given a context: we take the summed probability of all trees whose yield begins with the context-word (i.e., the prefix probability for context-word) divided by the summed probability of all trees whose yield begins with the context (i.e., the prefix probability for context).

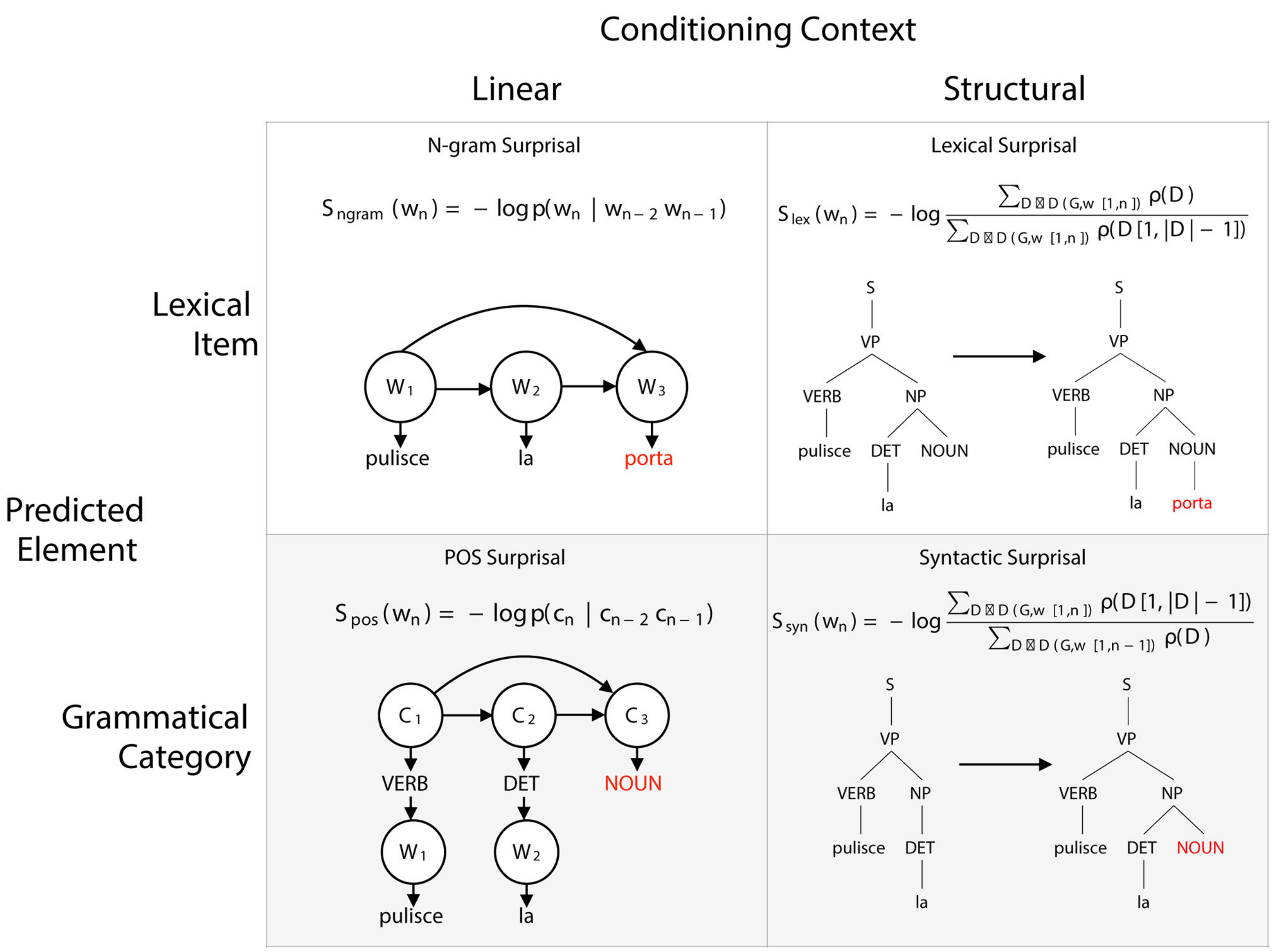

FIGURE 1
Models of surprisal. The two dimensions of language models (linear vs. hierarchical structure and word vs. category prediction). A choice in each dimension yields a distinct model of language, from which we can extract probability values.

PCFGs of this form suffer from being unable encode dependencies between lexical items: the choice of the verb in a VP is made independently of the choice of the noun in the verb's NP object. A body of work in the literature in natural language processing has addressed this shortcoming by adding 'lexicalization' to a PCFG, and this is the approach we adopt, following (Roark et al., 2009).

1.2. Dimension 2: word vs. category prediction

As already noted, n-gram models with longer contexts suffer from an estimation problem: it is impossible to get accurate estimates of the likelihood of relatively infrequent words in contexts that are defined by sequences of, say, 5 words. We can avoid this problem by incorporating another aspect of abstract linguistic structure: the categorization of words in part-of-speech (POS) classes. We can define a POS n-gram model as one where both the context (and the predicted element are POS (e.g., noun, verb, determiner, etc.,). To compute the surprisal of a word w, then, equation (Attneave, 1959) becomes:

$$p_{POS}(w|w_c) = \frac{count\ (c_c,\ c)}{count\ (c_c\ )}) \tag{3}$$

where c_c is the POS of the context, and c is the POS of the target word.

This is what we use for our model of **POS surprisal**.

With a small set of POS labels, the probability values for longer n-grams can be accurately estimated. Note though that POS n-gram model is insensitive to the meaning of individual words, so it will be unable to distinguish the probability of "cat" and "magazine" occurring in any context, as they are both nouns, but could distinguish their likelihood from that of prepositions like "of" or adjectives like "furry". As a result, this model's predictions for surprisal will differ from those of a word-based surprisal model.

Roark et al. (2009) propose a method for separating between word vs. category prediction in the context of a hierarchy-sensitive probability models. Specifically, for the category predictions, the prefix probability of the context-word sequence omits from the probability of the generation of the word. Following Roark et al., we call the resulting surprisal predictions Syntactic Surprisal. For word predictions, on the other hand, the context includes not only that contributed by the preceding words, but also the structure up to, but not including, the generation of the word. Again following Roark et al. (2009), we call the surprisal values computed in this way Lexical Surprisal.

2. Challenging data

In order to test different types of surprisal models a new set of stimuli has been designed building on Artoni et al. (2020). In that work the neural decoding of linguistic structures from the brain was found in carefully controlled data, where confounding factors such as acoustic information were factored out distinguishing this work from previous in the field such as in Frank et al. (2015), Brennan and Hale (2019), Shain et al. (2020). Specifically, their stimuli involved pairs of sentences sharing strings of two words with exactly the same acoustics (*homophonous phrase*, hence HP) but with completely different syntax. This strategy was made possible by relying on the properties of the Italian language. HPs could be either a Noun Phrase (NP) or a Verb Phrase (VP), depending on the syntactic structure that is involved. More specifically, HPs contained two words, such as *la porta* [la'pɔrta]: a first monosyllabic word (e.g., *la*) which could be interpreted either as a definite article (Eng. "the$_{fem.sing}$") or an object clitic pronoun (Eng. "her"); a second polysyllabic word (e.g., *porta*) which could be interpreted either as a noun (Eng. "door"), or a verb (Eng. "brings"). The whole HP could be interpreted either as a NP ("the door") in *Pulisce* ***la porta*** *con l'acqua* (s/he cleans **the door** with water) or as a VP ("brings her") in *Domani* ***la porta*** *a casa* (tomorrow s/he brings her home) depending on the syntactic context within the sentence where they were pronounced. Crucially, there is a major syntactic difference between NPs and VPs even though they are pronounced in exactly the same way: in NPs the article is base generated on the left; in VPs, instead, the clitic is base generated on the right and it is then moved to the left, a syntactic operation called "cliticization" (Moro, 2016). Indeed, in Artoni et al. (2020) two different electrophysiological correlates have been found in multiple cortical areas in both hemispheres, including language areas, factoring sound out, for NPs and VPs. However, a potential problem remained as to how surprisal could interfere with the measure of syntactic information. In fact, the linguistic material preceding HPs was different in the NPs vs. VPs interpretation, such as in ***Pulisce*** *la porta* (**s/he cleans** the door) vs. ***Domani*** *la porta* (**tomorrow** s/he brings). These stimuli have been revised and refined: three novel experimental conditions have been generated by modulating the syntactic context preceding HPs, as followes:

(i) ***unpredictable*** **HPs** (UNPRED): the syntactic context preceding HPs allows both NPs and VPs since it is an adverb. Therefore, the syntactic types of HPs are not predictable at the beginning of the sentence, but only after the HPs: if HPs are followed by verbs (such as in ***Forse*** *la porta è aperta*, "Maybe the door is open") they realize NPs, otherwise they realize VPs (***Forse*** *la porta a casa*, "Maybe s/he brings it at home"). Since the lexical context preceding HPs is exactly the same for both NPs and VPs, no differences in the surprisal value can be detected at the HP.

(ii) ***Strong predictable HPs*** (Strong_PRED): the syntactic context preceding HPs allows either NPs or VPs (but not both) and, therefore, the syntactic type of HP is predictable at the beginning of the sentence: if HPs are preceded by verbs, they realize NPs (such as in ***Pulisce*** *la porta con l'acqua*, "S/he cleans the door with water"); if HPs are preceded by nouns, they realize VP (such as in ***La donna*** *la porta domani*, "A woman brings her tomorrow"). This was the kind of stimuli exploited in Artoni et al. (2020), where the lexical context preceding HPs was different in NPs and VPs, allowing different surprisal values in the two cases.

(iii) ***Weak predictable HPs*** (Weak_PRED): the syntactic context preceding HPs allows both NPs and VPs, as in the *unpredictable* HPs, thus the first word of the HP (*la*) could either be an article or a clitic pronoun, but the second word of the HP (*porta*) can only be analyzed as a noun (door), as in 1st class predictable HPs, since the temporal adverb introducing the sentence (such as *ieri*, "yesterday") requires a past tense whereas the verbal form of the HP displays a present tense (brings) (such as ***Ieri*** *la porta era aperta*, "Yesterday the door/*brings it was open"). As in the unpredictable class, the surprisal value is eliminated by the lexicon preceding HPs, which is the same for both NPs and VPs (only the morphosyntactic shape of the second HP word forces the interpretation forward the NP).

A total of 150 trials were prepared: 60 for UNPRED-HPs, 30 UNPRED-NPs and 30 UNPRED-VPs, 60 for Strong_PRED-HPs, 30 Strong_PRED-NPs and 30 Strong_PRED-VPs, and 30 for Weak_PRED-HPs, only Weak_PRED-NPs since there cannot be VPs of this type.

3. Statistical analysis

We performed statistical analysis on the surprisal values calculated using the N-gram, Lexical, POS, and Syntactic surprisal of the 5 classes of stimuli (Strong_PRED-NP, Strong_PRED-VP, Weak_PRED-NP, UNPRED-NP, UNPRED-VP) relative to the first and the second word of the HPs. This analysis aimed at identifying the statistical language model that best differentiated between various linguistic stimuli in the same way as a human listener would do (e.g., distinguish Strong_PRED-NP and Strong_PRED-VP but not UNPRED-NP and UNPRED-VP).

Kruskal-Wallis tests revealed significant differences across the surprisal values associated with all five classes for all notions of surprisal. For the nouns and verbs, the difference was significant only for the POS surprisal and the syntactic surprisal. We further investigated these differences using Conover *post-hoc* tests with Holm-Bonferroni correction. For the articles and clitics, only the syntactic surprisal captured the difference across all three classes of predictable items ($p < 0.0001$, Figure 2A, top row). The POS and N-gram surprisal values of the articles were lower than those of the clitics ($p < 0.05$), while the lexical surprisal values of the articles of the Strong_PRED-NP sentences were lower than the lexical surprisal values of the articles of weak_PRED-NP sentences and the clitics of Strong_PRED-VP sentences. For nouns and verbs, both the POS surprisal and the syntactic surprisal showed a difference

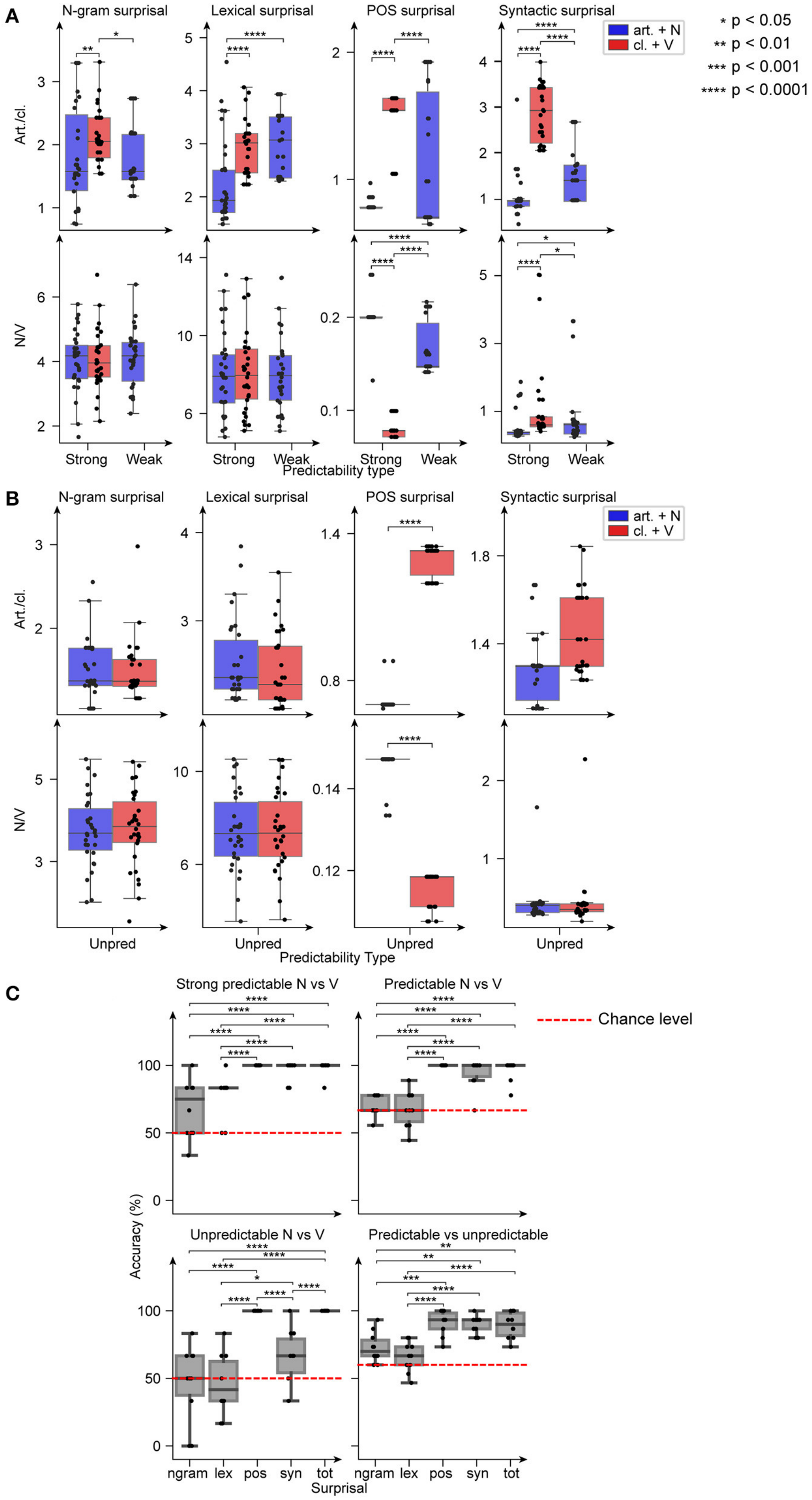

FIGURE 2
Statistical analysis and decoding. **(A)** Boxplots of the surprisal values for the (strong and weak) predictable items for the articles/clitics (art./cl., top row) and the nouns/verbs (N/V, bottom row). Each column represents a distinct notion of surprisal. **(B)** Same as (A) but for unpredictable (Unpred) items. **(C)** Boxplots of the accuracies for the distinct classification tasks using different sets of features. Each data point is the accuracy of 1 fold in a 10-fold cross validation procedure. The red dashed lines are the chance levels. Strong Predictable N vs. V: classification task (i). (Strong and weak) Predictable N vs. V: classification task (ii). Unpredictable N vs. V: classification task (iii). Predictable vs. unpredictable: classification task (iv). For each set of features both the surprisal of the article/clitic and of the noun/verb were considered. The set of features are: ngram – N-gram surprisal; lex – Lexical surprisal; pos – POS surprisal; syn – Syntactic surprisal; tot – all of the above.

between all three stimuli classes ($p < 0.05$, Figure 2A, bottom row). There was no difference between the N-gram surprisal values or lexical surprisal values of nouns and verbs. For the unpredictable items, only the POS surprisal values were different between the articles and clitics and between the nouns and verbs (Figure 2B).

We defined four different classification tasks: Strong_PRED nouns vs. verbs (i), predictable (Strong_PRED and Weak_PRED) nouns vs. verbs (ii), UNPRED nouns vs. verbs (iii), and predictable items vs. unpredictable items (iv). For each classification task we trained and validated (10-fold cross validation) one Support Vector Machines (SVM) for each notion of surprisal (i.e., using the values calculated according to the given notion of surprisal as features), and one SVM trained on all surprisal values regardless of the surprisal type, called tot-SVM. For classification tasks (i), (ii), and (iv), the SVMs trained on POS surprisal, Syntactic surprisal, and the tot-SVM reached near 100% accuracy, above the other two classifiers ($p < 0.05$, Conover post-hoc with Holm-Bonferroni correction). For classification task (iii), tot-SVM and the POS surprisal-trained SVM reached 100% accuracy, while Syntactic surprisal-SVM achieved slightly above-chance accuracy (Figure 2C).

4. Discussion and conclusion

In this paper four different probability models of surprisal have been compared by exploiting the following contrasting factors: words vs. parts-of-speech and sequences vs. hierarchical structures. In order to test these models three experimental conditions have been generated by modulating the surprisal context: those where the phrase was completely unpredictable by the contexts (unpredictable phrases), those where the phrase was immediately predictable by the first word of the phrase (strong predictable phrases), and those where the phrase was predictable only after the second word of the phrase (weak predictable phrases). Notably, all confounding factors, including acoustic information, were factored out distinguishing our work from previous in the field such as in Frank et al. (2015), Brennan and Hale (2019), Shain et al. (2020). We found that only those models combining hierarchical structures and part-of-speech categories successfully distinguished the three classes. On the other hand, surprisal models that only considers sequences of both words and parts-of-speech fail to replicate the expectation associated to the three classes. All in all, our modeling results point to the conclusion that statistical surface distributions are insufficient for capturing subtle distinctions in linguistic patterns.

Conspicuously absent from our discussion of language models are ones based on deep neural networks. Apart from their enormous success in practical tasks in natural language processing [e.g., as seen with the large language models (LLM) underlying systems like ChatGPT (Floridi and Chiriatti, 2020)], such models have also been used to model neural activity during sentence processing *via* the surprisal values they provide (Goldstein et al., 2022; Heilbron et al., 2022; Russo et al., 2022). On the surface, it would appear that such models belong to the class of linear lexical models (on a par with n-grams), as they do not appear in embody any sort of linguistic abstraction. As such, their success in modeling neural activity would provide a counter-example to the claims in this paper. However, because of their complexity, the factors governing the behavior of such models is quite obscure, and indeed studies of the internal representations of some of these models has found that they do indeed encode linguistic abstractions, incorporating both grammatical categories and hierarchical structure (Lin and Tan, 2019; Tenney et al., 2019; Manning et al., 2020). Yet, because of their complexity, it is virtually impossible to determine the precise role played by such abstractions in the computation of word probabilities, and for this reason we leave these models aside.

Eventually, it is important to note that the work reported here does not take into account brain data: the preliminary goal chosen here, in fact, is rather to determine what properties a statistical model of language needs to have in order to distinguish among different types of linguistic stimuli modulating surprisal. Nevertheless, our research does lead to a better comprehension of brain data as well: for example, the electrophysiological data observed in Artoni et al. (2020), as considered under the novel perspective proposed here, show that for those brain data to be fully understood, syntactic notions must necessarily be included in surprisal models.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization and funding acquisition: AM. Methodology: MG, AC, FA, and RF. Visualization: AC and RF. Supervision, writing—original draft, and writing—review and editing: MG, AC, FA, RF, and AM. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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The neurofunctional network of syntactic processing: cognitive systematicity and representational specializations of objects, actions, and events

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Theoretical accounts of syntax are broadly divided into lexicalist or construction-based viewpoints, where lexicalist traditions argue that a great deal of syntactic information is stored in lexical representations, while construction-based views argue for separate representations of multiword syntactic structures. Moreover, a strict autonomy between syntactic and semantic processing has been posited based on the grammatical well-formedness of non-sense sentences such as *This round table is square*. In this paper, we provide an overview of these competing conceptions of syntactic structure and the role of syntax in grammar. We review converging neuroimaging, electrophysiological, behavioral, electrocorticographic, and computational modeling evidence that challenge these views. In particular, we show that a temporal lobe ventral stream is crucial in processing phrases involving nouns and attributive adjectives, while a dorsal stream involving left parietal regions, including the angular gyrus, is crucial in processing constructions involving verbs and relational adjectives. We additionally support this interpretation by examining divergent pathways in the visual system for processing object information and event/spatial information, on the basis of integration across visual and auditory modalities. Our interpretation suggests that combinatorial operations which combine words into phrases cannot be isolated to a single anatomical location, as has been previously proposed—instead, it is an instantiation of a more general neural computation, one that is implemented across various brain regions and can be utilized in service of constructing linguistic phrases. Based on this orientation, we explore how abstract syntactic constructions, such as the transitive construction, both mirror and could emerge from semantics. These abstract construction representations are argued to be distinct from, and stored in regions functionally downstream from, lexical representations of verbs. Comprehension therefore involves the integration of both representations via feedforward and feedback connections. We implicate the IFG in communicating across the language network, including correctly integrating nominal phrases with the overall event representation and serving as one interface between processing streams. Overall, this approach accords more generally with conceptions of the development of cognitive systematicity, and further draws attention to a potential role for the medial temporal lobe in syntactic behaviors, often overlooked in current neurofunctional accounts of syntactic processing.

KEYWORDS

comprehension, syntax, semantics, combinatorial processing, neural oscillations, schemas, cognitive maps, cortical organization

1. Introduction

The combinatorial nature of language allows us to make infinite messages from a finite number of smaller elements. However the mechanisms by which we combine words into phrases and phrases into sentences has been the subject of decades of theorizing, experimentation, and retheorizing, yet with still little consensus. In this article, we briefly review two long standing debates in the field of theoretical syntax, namely the relationship between syntax and semantics, and the debate between lexicalist and constructionist theories. This frames our subsequent review of data predominantly from neuroimaging studies of syntactic processing during comprehension, with particular attention to the issue of combinatorial phrase building. We note an apparent pattern whereby primarily nominal-involved phrases appear to be processed in different regions than do primarily verb-involved phrases and those involving relational adjectives; we explain this by reference to visual processing of objects vs. actions and events. We therefore argue for a dual-stream model of syntactic processing that is divided into a ventral stream specialized for processing phrases involving entity nouns and attributive adjectives and a dorsal stream specialized for processing phrases involving verbs and relational adjectives. The ventral stream culminates in the left anterior temporal lobe (ATL) and the dorsal stream in the left angular gyrus (AG), with interactions between them occurring directly and mediated through the left inferior frontal gyrus (IFG). This suggests a distributed computation for combining phrases, accomplished using a delta-theta-gamma oscillatory "code." To combine phrases into sentences, we suggest a type of cognitive map might be involved, which may come about based solely on statistical regularities between constituents or may be augmented by event semantics abstracted as schemas. We argue that as a result of this conceptualization semantics constrains and scaffolds syntax. We further argue that this is in line with a construction-based view of syntax, while acknowledging the necessity of integrating lexicalist and constructionist views to more holistically account for the wide range of experimental findings that support both.

2. Syntax in linguistic theory

2.1. Autonomy of syntax and semantics

Sentences such as Chomsky's infamous *Colorless green ideas sleep furiously* or *This round table is square*, discussed decades prior by Benedetto Croce and Antonio Gramsci, suggest that semantic meaningfulness is not a necessity for syntactic well-formedness. Yet, whether such anomalous cases should be seen as representative of language as a whole, and how syntax and semantics relate more generally, remains a matter of debate. Theorists working in the Generative Grammar tradition have typically held that syntactic and semantic knowledge are processed in two autonomous modules, with the syntactic module feeding into the semantic module (Chomsky, 1981, 1995; Lasnik and Lohndal, 2010; Collins and Stabler, 2016). Meanwhile, in theories under the Construction Grammar umbrella, the relationship between syntax and semantics has been seen through the lens of the Saussurean sign-signified relationship, where syntactic constructions are signs signifying particular meanings (Goldberg, 1995, 2003, 2013). Both traditions view syntax as the basis for semantic interpretation, and while they also converge on interesting conclusions, there are important distinctions between them.

Generative theories conceptualize the syntactic and semantic modules as embodying processes delineated into separate modules, whereas Construction-based theories view semantics more as something that is represented by specific lexical, morphological, and syntactic signs. In the process-type view, a syntactic parse of a sentence is constructed, and the way that the parse is handled influences the ultimate interpretation—for example, in the sentence, *The Enterprise located the Romulan ship with long-range sensors*, the prepositional phrase [$_{PP}$ *with long-range sensors*] could be "attached" to the verb phrase to give an interpretation whereby the Enterprise used its long-range sensors to find the Romulan spacecraft. [$_{PP}$ *With long-range sensors*] could also be "attached" to modify the Romulan spacecraft, such that the interpretation is now that the Enterprise found (through some unspecified means) the Romulan spacecraft that possesses long-range sensors. This basic idea was extended through various iterations of Generative theory to suggest that the underlying configuration of sentences was the same, regardless of their surface form. Deviations from standard intransitive, transitive, and ditransitive templates were explained through movement operations, some motivated by different syntactic principles. Though small aspects of semantics were folded into the motivations behind syntactic phenomena, Minimalism still maintains a separation between the syntactic processing modules: semantic features are interpreted at the Conceptual-Intentional Interface, while syntax is a set of operations applied to linguistic objects in order to render them interpretable at both the Articulatory-Perceptual and Conceptual-Intentional Interfaces (Chomsky, 1995; Collins and Stabler, 2016). Nevertheless, semantics are ultimately seen as secondary to syntax, in the sense that semantic interpretations of a sentence depend on how the sentence is parsed syntactically.

Constructionist theories take the accepted sound-meaning relationship of morphemes a step further and propose that such relationships hold for multi-word constructions as well. Although both theories arrive at similar generalizations, namely that semantic interpretations depend on syntactic form, how they propose this relationship comes about is entirely divergent. Rather than proposing that the relationship is mediated by a certain hierarchical configuration endowed by Universal Grammar or a set of complex processes, Construction-based theories contend that the relationship between syntactic form and semantic interpretation arises through repeated pairings of form and meaning. Over time, these pairings are abstracted over to conventionalize a grammatical Construction which has an associated meaning. For example, sentences like *The Enterprise located the Romulan ship* are abstracted over with other sentences such as *The dog chased the cat*, *The CIA smuggled drugs*, and *The quarterback threw the ball* to generate a TRANSITIVE CONSTRUCTION specifying a subject NP[1] followed by a verb and an object NP; this structural form is then associated with a semantic interpretation roughly

1 The use of NP to denote these phrases is one of convenience and not a theoretical statement with respect to the DP/NP hypothesis.

equivalent to "the subject NP performed an action upon the object NP"[2]. Further subdivisions of these constructions based on more nuanced semantics and networks of related grammatical forms are also proposed. Despite representational and operational differences then, both theories propose a tight relationship between syntax and semantics whereby syntactic form determines semantic interpretation from a comprehender's perspective.

2.2. Lexicalist and construction-based theories

Another point of contention across theoretical frameworks is whether syntactic constructions are driven by lexical items or whether they are independent constructs, which lexical items are inserted into. In this section, we will briefly examine these two viewpoints broadly, while later in this paper we will argue that the evidence supports a unification of both views, in which we will discuss how syntactic constructions can be abstracted from lexical items and the syntactic distributions they participate in. Differences between the two types of theories are most apparent in their treatment of verb argument structure, so we will make use of such examples to illustrate.

Lexicalist theories, including those in the Generative tradition, propose that syntactic structure and information is determined by lexical information. The type and amount of syntactic information determined by the lexical entry may vary from theory to theory, but typically a lexical entry is said to contain information about the types of phrases the lexical item combines with (i.e., the valence information of a word). For example, a lexical entry for *cry* would include that it combines with an NP as its subject; a lexical entry for *write* would include that it combines with three NPs, one as its subject, one as its indirect object, and one its direct object. Lexical rules are proposed to alter a lexical item's entry and thereby its valence, in order to account for alternations in argument structure; for example, passive constructions are said to be derived from a passivization lexical rule that decreases a verb's valency by one, while verbs such as *give* which undergo the dative alternation will be acted upon by a lexical rule governing their realization in the double-object or prepositional-object forms. Abstract syntactic rules are used to combine lexical items into phrases, when licensed by their lexically-determined argument structures, as well as to combine phrases into clauses.

Constructionist theories, in contrast, propose a hierarchy of construction forms that include lexical items as well as more abstract syntactic structures, which (depending on the particular theory in question) may be independent of any particular lexical entry. These syntactic constructions are typically claimed to emerge as abstracted patterns of usage across multiple lexical items. While notational conventions vary widely, an INTRANSITIVE CONSTRUCTION for example may be represented as [Subj V], indicating that it is formed by a lexical item or phrase being inserted into the Subj slot and a verb lexical item into the V slot. This generalization can capture sentences like *The graduate student cried*, as well as sentences like *Immortal Technique's latest single slaps!* which would be considered peripheral in other theories or would require potentially theoretically undesirable explanations to account for. Alternations of argument structure are explained by verbs being inserted into different constructions: *transform* for example may be inserted into a TRANSITIVE CONSTRUCTION to yield a sentence such as *We transform them into intertwined vectors of struggle* or inserted into a PASSIVE CONSTRUCTION to yield a sentence such as *The live green earth is transformed into dead gold bricks*. As discussed above, Construction-based theories tend to propose inheritance networks between related constructions—the DOUBLE-OBJECT and PREPOSITIONAL-OBJECT constructions may be considered descendants of a more general DITRANSITIVE CONSTRUCTION in this framework, with different theories proposing varying amounts of information shared between ancestor and descendant constructions.

2 Semantic interpretations may be formalized in various ways in these theories, however, a full discussion of these formalisms is outside the scope of this paper.

3. Distributed neurofunctional network of syntactic processing

3.1. Combinatorial processing of nominal-type phrases

Investigations specifically of combinatorial processing of phrases have repeatedly shown selective activation of the ATL, as well as the left AG and occasionally ventromedial prefrontal cortex (vmPFC). These studies have tended to use similar types of minimal combinatorial units, typically consisting of a two word condition that forms a phrase compared to non-word+word pairs that are suggested to not form such phrases. Zaccarella and Friederici (2015) for example, report selective activation of the left IFG for determiner+pseudo-word noun pairs, while others such as Bemis and Pylkkänen (2011); Pylkkänen et al. (2014); Westerlund et al. (2015); Flick et al. (2018) and Phillips and Pylkkänen (2021) have often used adjective+noun and verb+noun pairs. In contrast to the results of Zaccarella and Friederici (2015) and Zaccarella et al. (2017), MEG studies consistently show activation of left ATL in combinatorial conditions involving adjective+noun pairs in comparison to non-word+noun pairs (Bemis and Pylkkänen, 2011; Pylkkänen et al., 2014; Westerlund et al., 2015; Flick et al., 2018; Phillips and Pylkkänen, 2021). While these results were initially considered to be a form of both syntactic and semantic combinatorial processing, a purely semantic explanation has been argued for recently (Pylkkänen, 2019). To try to reconcile these findings though, we might rely on the distinction between processing of adjuncts compared to arguments. This is of course a fundamental distinction in linguistic theory, with adjectives generally being considered adjuncts within noun phrases, and a noun considered an argument of a determiner in some theories of syntax (and vice versa in others).

However, Westerlund et al. (2015) examined similar determiner+noun combinations as Zaccarella and Friederici (2015), as well as verb+noun argument combinations, and still found activation of left ATL compared to non-word+noun combinations. Granted, the determiner+noun pairs used in

Westerlund et al. (2015) involved both real determiners and real nouns instead of the real determiners and pseudo-nouns of Zaccarella and Friederici (2015). While Friederici (2018) and others maintain that determiners are mostly semantically vacuous, Westerlund et al. (2015)'s results could be due to the semantic effect of combining a somewhat semantically meaningful determiner and a fully semantically meaningful noun. For example, *the* may have little semantic content, especially when combined with a phonologically plausible but non-meaningful pseudo-word; however, when combined with *manifesto*, it specifies that a particular manifesto is being referenced. This may be the driver of the combinatorial effects of determiner+noun seen in left ATL.

Westerlund et al. (2015)'s additional whole brain analysis further failed to show activation in the left IFG, left vmPFC, or in the left AG. Again, these findings suggest that the type of computation Zaccarella and Friederici (2015); Zaccarella et al. (2017), and Friederici (2018) identified as being carried out by left IFG may not be unique to that region or that its role in phrase-building is less straightforward. Nevertheless, consistent MEG results and even the fMRI meta-analysis conducted in Zaccarella et al. (2017) suggest a preference in the ATL for processing phrases involving nouns. Some additional clarity on this matter comes also from Murphy et al. (2022b), who investigated composition of minimal adjective+noun phrases using cortical surface electrocorticography (ECoG). They report a significant increase of high gamma (70–150 Hz) power in posterior superior temporal sulcus (pSTS) in combinatorial conditions shortly after the onset of the second word (100–300 ms), in addition to increases in power across the 8–30 Hz alpha and beta range in the IFG and ATL, and increased functional connectivity between pSTS and the IFG and pSTS and the ATL. The authors interpret these data as indicating that the pSTS is responsible for phrase composition, which is somewhat at odds with MVPA evidence suggesting the ATL as the locus of phrase composition (Baron et al., 2010). Nevertheless, the results of Murphy et al. (2022b) and Baron et al. (2010) are consistent with much of the MEG evidence already reviewed, as well as Baron and Osherson (2011) and Flick and Pylkkänen (2020). These data suggest a model in which the IFG serves as a working memory store that can reactivate the phonological representations in pSTS, generating a phrasal constituent through oscillatory activity (explored in more detail in Section 3.5.2.2), which is communicated to the ATL or AG (as explored in the next section) as appropriate to perform conceptual combinatorial computations. This functionality would also be in keeping with well accepted models of feed-forward/feedback reciprocal cortical connectivity (see also Flinker et al., 2015; for direct ECoG evidence in linguistic tasks), as well as evidence that predictions at higher levels of linguistic abstraction (e.g., syntactic category, semantics) inform or constrain predictions at lower levels (e.g., phonemes) (Lyu et al., 2019; Heilbron et al., 2022).

3.2. Combinatorial processing of phrases involving verbs

The AG has been previously proposed as processing verb argument structure or thematic role assignment. In particular, activation of AG increases parametrically with an increase in verb valency (Thompson et al., 2010); Meltzer-Asscher et al. (2013) used verbs that alternate in their valency (e.g., *bake*: *Neelix baked* vs. *Neelix baked pastries*), to show that AG was more active for verbs with higher valencies than for verbs with lower valencies. Adding to this evidence, Boylan et al. (2015) used Multi-Voxel Pattern Analysis (MVPA) to examine activation in bilateral ATL and bilateral AG, using stimuli sets similar in nature to those used by the Pylkkänen group's studies, i.e., verb+noun, verb+adverb, preposition+noun, and noun+adjective pairs, plus control sets of non-word+verb/verb+non-word and non-word+noun/noun+non-word pairs. They found significant similarity in the activation patterns elicited by verb+noun and verb+adverb pairs within left AG, but not in left ATL, and concluded that left AG appears sensitive to specifically verb+noun argument combination or perhaps the expectation for a verb+noun argument relationship.

These results are not irreconcilable with those of Westerlund et al. (2015), discussed above. Meltzer-Asscher et al. (2015) and Thompson et al. (2007, 2010) showed response in left AG and surrounding areas even in the absence of arguments, suggesting that there may have been roughly the same activation of left AG during the verb+noun pair and verb+non-word pair conditions. This contrast may have reduced any overall finding of left AG involvement in Westerlund et al. (2015). Moreover, Westerlund et al. (2015) used MEG whereas Boylan et al. (2015) used fMRI, and Westerlund et al. (2015) note that the time course for combinatorial-based left ATL activation peaks within 250 ms. The BOLD response of course takes several seconds to materialize, so given that the general trend of activation seen by Westerlund et al. (2015) was only distinguishable between the combinatorial and non-combinatorial conditions within a narrow time window of 200–400 ms, the sluggish BOLD response may render these distinctions unobservable with fMRI. Finally, only a subset of Westerlund et al. (2015)'s stimuli were verb+noun combinations and they were unable to test differences between determiner+noun and verb+noun stimuli. It's therefore unsurprising that, even if the left AG is sensitive to verb argument structure processing, Westerlund et al. (2015) did not see such activation, as they likely lacked the power to detect such an effect.

Nevertheless, Matchin et al. (2019) do contradict a *strict* argument-structure-based or thematic-role-assignment-based account of AG in favor of a more general conceptual-semantic, event-information account of AG processing. The authors used three word stimuli consisting of a verb+determiner+noun and determiner+adjective+noun trios; crucially, the adjective was the past participle of the same verb used in the verb-based trio, e.g., *surprised*, giving a possible VP trio such as *surprised the kitten* and an NP trio such as *the surprised kitten*. Using fMRI, they found activation in AG in both the VP and NP conditions, but with no significant difference between them; as in several prior studies though, they still found significant differences between activation in AG to phrases compared to lists.

Once again, these results are not necessarily irreconcilable with the previous literature reviewed—especially if we take a construction-based view of argument structure. Of course, the relationship between event semantics and argument structure is not necessarily straightforward and providing a definitive or exhaustively comprehensive account is beyond the scope of this paper. However, we suggest that this connection provides a strong starting point for a cognitively grounded understanding of argument structure and the interaction between syntax and semantics.

3.3. Where the twain do meet

Left IFG—i.e., Broca's area—has drawn significant previous attention for its potential role in syntactic processes. Matchin and Hickok (2020) view the process carried out by the IFG, particularly the pars triangularis, as morphosyntactic linearization of a structure. However, given the long history of interest localizing syntactic processing to IFG, it's worth exploring broad trends that have led to this conclusion. The IFG's theorized contribution was initially based on patients with Broca's aphasia who routinely omit function words in their production and who struggle with syntactically complex sentences (Schwartz et al., 1980; Caplan and Futter, 1986; Hickok et al., 1993; Mauner et al., 1993; Kolk and Weijts, 1996; Kiss, 1997). Due to the broad range of production deficits in these patients, the early view of Broca's area was as a general language output module.

Numerous studies have also found an increase in BOLD response in left IFG during processing of sentences with non-canonical word order, compared to sentences with canonical word order (Caplan et al., 2000; Ben-Shachar et al., 2003, 2004; Bornkessel et al., 2005; Friederici et al., 2006; Grewe et al., 2007; Shetreet et al., 2007; Kinno et al., 2008; Bornkessel-Schlesewsky et al., 2009; Santi and Grodzinsky, 2010; Burholt Kristensen et al., 2013; Shetreet and Friedmann, 2014, among others). The cited studies found greater activation for sentences such as *Picard piloted the Stargazer* (grammatical and canonical) in comparison to sentences like *The Stargazer, Picard piloted* (grammatical but non-canonical), across a small range of languages including English, German, Hebrew, Danish, and Japanese. Based on these studies, as well as others which saw involvement of left IFG during processing of long-distance dependencies, a number of researchers claimed that IFG was the site of the theoretical *Move-α* operation from Chomskyan theories of syntax (Ben-Shachar et al., 2003, 2004; Grodzinsky and Friederici, 2006; Grodzinsky and Santi, 2008; Santi and Grodzinsky, 2010). *Move-α* is an operation that was proposed to account for a variety of syntactic phenomena where certain constituents are displaced from their canonical positions—the example above, for instance (*The Stargazer, Picard piloted*) would be explained through a movement that fronts the object from its underlying canonical position after the verb. However, other research groups suggested that the aforementioned results were actually indicative of increased working memory demands (e.g., Rogalsky and Hickok, 2011, among others).

Additional studies have attempted to control for working memory effects (Röder et al., 2002; Ben-Shachar et al., 2003; Friederici et al., 2006; Kinno et al., 2008; Kim et al., 2009; Obleser et al., 2011; Meyer et al., 2012). Meyer et al. (2012) in particular used adverbial modifiers to dissociate long-distance processing and non-canonical word order processing in German. They reported increased activation of left IFG to object-first sentences, with no effect of distance detected in the pattern of IFG activation. They further found that there was no correlation between IFG activation and subjects' performance on a digit span working memory test. Together, these results were taken as confirmation that the activity was driven by syntactic ordering effects rather than working memory. Nevertheless, there are some important caveats: the first being that the digit span task may not represent the best measure of verbal working memory, and we might expect stronger correlation between scores on a measure like the reading span task and IFG activation instead. Secondly, the conceptualization of working memory Meyer et al. (2012) argue against is more of an active, subvocal rehearsal working memory, rather than a more passive temporary storage (which is also sometimes distinguished as short-term memory) (Schwering and MacDonald, 2020). Thirdly, this result might be expected under a filler-gap dependency model of movement, where a linguistic item is kept in working memory until the comprehender encounters a syntactic gap, which is filled with the item being held in working memory and allows for interpretation (Fiebach et al., 2001). Fourthly, while Meyer et al. (2012) note that some studies which attempted to control for working memory effects involved English, most have used case marking languages such as German, Hebrew, and Japanese because the ordering flexibility allows for better separating distance and ordering effects. That said, the addition of case marking may influence processing strategies compared to the results from English, so the extent to which results in German, Hebrew, or Japanese generalize is unknown. Finally, results from an fMRI study contrasting double-object and prepositional-object dative sentences in English found no significant difference in activation of the IFG between the two sentence types (Allen et al., 2012). Given the additional phrasal embedding required under a more Generative framework for the prepositional-object construction, it might be expected for the IFG to be more activated in this condition.

More specific hypotheses regarding the role of particular subregions in left IFG have been proposed as well, based on differential activation patterns seen in some of these previous studies. These hypotheses propose that Brodmann's Areas (BA) 45 and 47 subserve semantic processes, that frontal operculum engages in building of local adjacent dependencies, and that BA 44 is involved in building non-adjacent syntactic hierarchies (Friederici, 2016). Zaccarella, Friederici, and colleagues argue that BA 44 in particular is the location of the theoretical *Merge* operation, based on the evidence discussed above, yet this is challenged on both theoretical and empirical grounds by other researchers. Nevertheless, despite the broad range of specific interpretations, activation of left IFG during comprehension of non-canonically ordered sentences has been a consistent finding. A potentially more general role for the IFG in language processing may provide a more comprehensive interpretation of these results, and is also suggested by ECoG data showing that the IFG mediates the communication of linguistic information between temporal cortex and motor cortex (Flinker et al., 2015). Taken together, these results are suggestive of a broad role for the IFG in communicating between regions of the language network, which can facilitate a range of linguistic computations including combinatorial phrase building and encoding motor representations for language production.

In reviewing lesion symptom mapping studies for possible evidence of IFG involvement in syntactic processing, Matchin and Hickok (2020) note inconsistent findings that damage to IFG results in comprehension deficits. This does not necessarily mean that the IFG is completely uninvolved in comprehension; given that language processing involves bottom-up and top-down mechanisms, relying on a dorsal stream from primary auditory cortex to AG and back may be sufficient. However, in the remainder of this section, we argue that part of the IFG's role in comprehension processing of sentences with non-canonical word orders is ensuring that nouns are correctly mapped to the appropriate semantic roles. To make this argument however, we first need to discuss the role of the posterior superior temporal sulcus (pSTS) and posterior superior temporal gyrus (pSTG).

Especially given their anatomical proximity to primary auditory cortex, these regions have typically been thought to be involved in phonological and lexical representations (Hickok and Poeppel, 2007; Pasley et al., 2012, see also Hickok (2022) for a review). However, portions of these regions have also been implicated in semantic processing by Frankland and Greene (2015, 2020) and by Murphy et al. (2022b), discussed above. Frankland and Greene (2015) used MVPA of fMRI data to suggest that separate areas of left mid-superior temporal cortex act as temporary storage of the agent and patient of a sentence, independent of their syntactic position. Frankland and Greene (2015, 2020) involved pairs of transitive sentences (e.g., *Picard evacuated the Romulans/the Romulans evacuated Picard*) and their passive forms, (e.g., *The Romulans were evacuated by Picard/Picard was evacuated by the Romulans*), thereby varying which participant was the agent and which the patient, as well as separately varying which side of the verb the agent and patient appeared on. Frankland and Greene (2015) used a classifier form of MVPA, which tries to divide data points into two or more distinct, predetermined categories. Using this classifier, they identified mid-superior temporal cortex that discerns between mirror pairs of transitive sentences; within this region, they further identified an upper portion of left STS and a portion of posterior STS which selectively activates to agents, and a separate portion of upper left STS extending to left lateral STG which selectively activates to patients. Similar follow-up fMRI work in Frankland and Greene (2020) confirmed these results, as well as providing evidence that more verb-specific semantic roles (e.g., a chaser rather than the more general agent) activate anterior-medial prefrontal cortex (i.e., BA 10) and concomitantly deactivate the hippocampus.

Some complicating results though come from Matchin et al. (2019), who reported increased activation of the pSTS for the verb phrase stimuli compared to the noun phrase stimuli, interpreting this as evidence that the pSTS encodes syntactic argument structure via lexical subcategorization information—or that the contrast could be driven by frequency effects if the verb use is more frequent than the adjectival use. However, given that *the boy* is assigned a semantic role in the verb phrase condition but not the noun phrase condition, this result can be seen as somewhat supporting Frankland and Greene (2015, 2020)'s contention that areas of superior temporal cortex represent broad semantic arguments of verbs. Contradicting this interpretation though is Frankland and Greene (2019), where the authors re-analyzed their prior data from Frankland and Greene (2015), reporting a region of left middle temporal gyrus (MTG) that specifically activates in response to verb and patient combinations, but not agent and verb combinations. Moreover they suggest that activation in an additional region of left MTG is predicted by the combination of agents and verb+patient combinations. Taken together, these results suggest an asymmetry in verb-argument semantic processing that functionally reproduces a syntactic hierarchy. Despite this, the pSTS activation reported by Matchin et al. (2019) for VPs involving a verb and patient does not accord with Frankland and Greene (2015)'s identification of this as an agent-selective region.

Returning to the IFG's role, the types of sentences that patients with Broca's aphasia were reported to have difficulty comprehending were passives—where the typical semantic role assignment of an active transitive is reversed—or sentences with increased levels of clausal embedding—which similarly involve disentangling which noun is assigned to what semantic role (Berndt et al., 1996). Furthermore, patients with damage to regions of the IFG, the arcuate fasciculus, the extreme capsule, and posterior temporal lobe can show impairments in processing semantically reversible sentences (e.g., *Janeway hugged Chakotay/Chakotay hugged Janeway*, where the semantics of the sentence allow for either entity to be the agent or the patient) (reviewed in Blank et al., 2016). The arcuate fasciculus connects the pars opercularis portion of the IFG to the pSTG while the extreme capsule connects the pars triangularis portion of the IFG to the pSTG (Makris et al., 2005; Friederici et al., 2006; Frey et al., 2008). The inconsistent pattern of damage in IFG leading syntactic comprehension impairments then could be explained by whether portions of IFG that are connected to pSTG via the arcuate fasciculus or extreme capsule are damaged. Given the type of impairment, i.e., that semantic role assignment seems to be impacted, the IFG therefore seems to play a role in correctly mapping nouns to the appropriate portion of pSTG/pSTS that indexes the semantic roles of a sentence. This could be performed through either language-specific processes or through domain-general working memory processes—or both. This explanation also explains that the same impairment is seen when there is a lesion to the connecting fiber tracts or to the pSTG itself and is consistent with the broad role of the IFG proposed above.

It is important to note some of the limitations and contradictions in the evidence for this proposal though. Frankland and Greene (2015, 2019)'s verb stimuli consisted of items like *chase*, which may exert less semantic selectional restrictions on their agents than a verb like *melt* does—leaving the possibility that their results may not generalize to all verbs. Furthermore, it is unclear how to reconcile the Matchin et al. (2019) and the Frankland and Greene (2015, 2019, 2020) interpretations of left STS, MTG, and even parts of STG with their previously implicated involvement in spectro-temporal auditory processing and lexical access[3] (Hickok and Poeppel, 2007). Despite this, Frankland and Greene (2015, 2019, 2020) and Matchin et al. (2019) are not the only studies to report activation of left pSTS, pSTG, or left MTG during sentence-processing tasks with syntactic manipulations between conditions

3 For example, although the stimuli in these studies were written words, there may also be some activation of low-level phonological features of the words subjects read (and potentially also rehearse).

(e.g., Ben-Shachar et al., 2003, 2004; Bornkessel et al., 2005; Grewe et al., 2007; Assadollahi and Rockstroh, 2008; Kinno et al., 2008; Kalenine et al., 2009; Santi and Grodzinsky, 2010; Pallier et al., 2011).

3.4. Interim summary

It is useful at this point to provide a brief summary of the evidence and analysis we have so far reviewed. This information is condensed in Table 1, but we sketch them here in narrative form as well. While we are primarily focused on syntactic processing in this paper, some of the results pertaining to semanti c processing are pertinent as well, given both the connection between the two as well as the difficulty in definitively dissociating the two experimentally. This is particularly relevant in the discussion surrounding the left ATL and left AG, both of which have been variously claimed to be sensitive to primarily syntactic or primarily semantic information.

With this in mind, based on MEG and fMRI data comparing two-word phrases to pairs of non-words and real words, left ATL has been argued to contribute primarily to *semantic* processing by *conceptually* combining the meanings of multiple words together; however, ECoG data utilizing similar types of stimuli have implicated ATL instead in predictive processing. Left AG has likewise been argued to be *the* focal point of semantic-conceptual combinatorial processing, given similar types of fMRI and MEG studies. It has also been argued to store verb argument structure representations or to process the thematic roles assigned by verbs, given fMRI studies showing increased activation as a function of verb valency (with and without the accompanying arguments), as well as similarity in the activation patterns elicited by phrases involving verbs, revealed by MVPA. Following extensive fMRI and PET studies manipulating the relative ordering of constituents in a sentence, the size of constituents, contrasts between determiner+pseudo-noun pairs and word lists, and contrasts between determiner+pseudo-noun pairs and determiner+non-word pairs, the left IFG has been argued variously to be the locus of syntactic phrase building or the locus of a syntactic movement operation. ECoG data has suggested instead that IFG is involved in predictive processing and in communicating linguistic information between cortical regions—which, it should be noted, are not mutually exclusive functions.

In reviewing some of the aforementioned studies on syntactic processing, Matchin and Hickok (2020) interpret increased activation of the posterior MTG for sentential compared to word list stimuli as indicative that the pMTG stores hierarchical tree structures headed by lexical items, reminiscent of Lexical Tree-Adjoining Grammar (Schabes et al., 1988), though this interpretation also accords with the Memory-Unification-Control model of Hagoort (2013). The final major anatomical region we discussed was the mid superior temporal cortex, within which Frank et al. (2015); Frankland and Greene (2019, 2020) reported small clusters that were preferentially active to nouns functioning as agents or as patients, as evidenced from MVPA of fMRI data, using stimuli that used the same nouns as agents and as patients.

While there have been some consistent findings amongst this literature, some of the interpretations appear to be conflicting and even contradictory. We therefore turn now to how we might make better sense of this data, drawing upon the cognitive neuroscience literature of other domains, especially vision. We do so under the premises that, (1) from an evolutionary perspective, anatomy and physiological mechanisms are frequently repurposed for new uses; and (2) from the perspective of neural organizational and resource efficiency, populations of neurons encoding or processing similar information should be in close physical proximity.

3.5. Making sense of these divisions

3.5.1. Dual stream in visual processing and representations

Processing of visual sensory information has long been accepted as branching into two "streams", even if the exact information processed by each has been subject to disagreement (Mishkin et al., 1983; Goodale et al., 1991; Goodale and Milner, 1992). The ventral stream involves a series of brain regions extending ventrally from the occipital cortex along the inferior temporal lobe bilaterally, and appears to process and represent the sensory information of objects (Mishkin et al., 1983; Goodale et al., 1991; Goodale and Milner, 1992). The dorsal stream involves regions of posterior parietal cortex, though its function has been somewhat more controversial—in general however, it has shown sensitivity to manipulations of actions, events, and spatial relationships between objects (Mishkin et al., 1983; Goodale et al., 1991; Goodale and Milner, 1992). There is also evidence that lexical representations, while still fairly diffusely represented, may follow similar patterns (Yang et al., 2017; Lukic et al., 2021).

3.5.2. Higher level cognitive systematicity

3.5.2.1. Integrating cognitive representations across sensory domains

While we can certainly use language to talk about more abstract concepts or imaginary things, a great deal of our language use—especially during early childhood acquisition—is centered on our material reality. Indeed, core functions of (spoken) language require binding auditory labels to visual information such as objects, allowing us to communicate about the things in our environment. The relationships between objects and the actions we perform on them are similarly important for both our visual perception of the environment and how we communicate about them. With that said, we wish to be clear that we are making an argument more in keeping with a "weak" embodied view of language processing, in that labeling of visual information with linguistic information is certainly important for language acquisition, but is not to say that language comprehension works necessarily (or solely) by activating additional sensory perception processing areas.

Nevertheless, there is some evidence for individual variation in the amount of activation of visual sensory processing areas during linguistic processing (e.g., Humphreys et al., 2013). Humphreys et al. (2013) show greater activation of the posterior superior and middle temporal gyri (MTG) for visual scenes with motion compared to static visual scenes, which is shared with

TABLE 1 Summary of anatomical regions implicated in syntactic or semantic processing, including the function each region is claimed to carry out and the evidence commonly cited to support these interpretations.

Anatomical region	Purported function(s)	Evidence
Left ATL	Semantic combinatorics; syntactic combinatorics; predictive processing	Two-word phrases > non-word+word pairs, two-word phrases > word lists (Bemis and Pylkkänen, 2011; Pylkkänen et al., 2014; Westerlund et al., 2015; Flick et al., 2018; Phillips and Pylkkänen, 2021); increased power in the 8–30 Hz range (Murphy et al., 2022b)
Left AG	Semantic combinatorics; syntactic combinatorics; argument structure representations	Increased activation as a function of arguments taken by a verb (Thompson et al., 2007, 2010; Meltzer-Asscher et al., 2015); similarity in activation patterns for phrases involving verbs (Boylan et al., 2015); verb+noun phrases = verb-derived adjective+noun phrases (Matchin et al., 2019); multiword phrases > word lists (Bemis and Pylkkänen, 2011; Pylkkänen et al., 2014; Matchin et al., 2019)
Left IFG	*Merge*, i.e., syntactic combinatorics; syntactic movement; predictive processing; communication between language-involved cortical areas	Determiners+pseudo-nouns > word lists; determiners+pseudo-nouns > determiners+non-words (Zaccarella and Friederici, 2015; Zaccarella et al., 2017; Friederici, 2018); non-canonically ordered sentences > canonically ordered sentences (Caplan et al., 2000; Ben-Shachar et al., 2003, 2004; Bornkessel et al., 2005; Friederici et al., 2006; Grewe et al., 2007; Shetreet et al., 2007; Kinno et al., 2008; Bornkessel-Schlesewsky et al., 2009; Santi and Grodzinsky, 2010; Meyer et al., 2012; Burholt Kristensen et al., 2013; Shetreet and Friedmann, 2014, among others); increased power in the 8–30 Hz range (Murphy et al., 2022b); systematic increases in high gamma power proceeding from pSTS to IFG to motor cortex, Granger causal analysis showing feed-forward and feedback functional connectivity between the three cortical regions (Flinker et al., 2015)
Left pMTG	Lexical access; storing hierarchical lexical tree representations	Sentences > word lists (reviewed in Matchin and Hickok, 2020)
Left mid superior temporal cortex	Indices of semantic role	Specific clusters selectively active for agents vs. patients identified using MVPA (Frankland and Greene, 2015, 2019, 2020)
Left pSTS	Semantic combinatorics	Adjective+noun > adjective+pseudoword and pseudoword+noun, electrodes selectively active in early time windows for adjective+noun stimuli (Murphy et al., 2022b)

linguistic processing. Visser et al. (2012) too shows activation of pMTG for concordant lexical items and images (though cf. Murphy et al. (2022b) for evidence of these types of stimuli instead activating regions of frontal cortex and insula). This shared neural substrate suggests that it serves to associate representations across modalities. Indeed, a study by Pritchett et al. (2018) argued against such a strongly embodied account of language based on neuroimaging data that lacked activation in brain regions linked to higher-level language processing—except for the AG, which, as we will argue in Section 3.5.3, is what we would expect. This therefore doesn't necessarily rule out a role for visual sensory representations being involved in language comprehension according to an embodied cognition view, but does rule out the most extreme version of the argument where lower-level visual sensory processing areas are involved; conversely, it could be taken to suggest activation of linguistic representations during visual processing, in essence understanding what we see by putting it into language. The model we propose here though does not require association of sensory information across the auditory and visual systems to perform the functions we assign them. Instead, we argue that the brain is organized to facilitate efficient association across modalities when available, and this intrinsic organization supports the syntactic processing functions we have assigned to brain regions, even in the absence of one or more modality. In such situations, the exact anatomical regions performing the various syntactic functions may vary based on the input actually being received and competition among modalities to make use of cortical tissue not otherwise utilized. Yet this variation should still be somewhat constrained by the layout specified genetically and instantiated during development.

3.5.2.2. Combinatorial processing in linguistic representations and beyond

As mentioned above, some (e.g., Friederici, 2018) have proposed isolating the syntactic combinatorial operation to the left IFG. The problem of localizing this process is not simple given the various brain regions we have reviewed which have been implicated in phrase building. We instead propose that combinatorial operations are subserved by an instantiation of neural processes used in other cognitive domains and that the search for a single localizable brain region responsible for carrying out these operations may not be as productive a hypothesis space. Viewing phrase building as a computation that may not have a single neural correlate allows us to look for competing putative mechanisms to test that may better explain the current data. A strong candidate mechanism is hierarchically organized cross-frequency coupling of oscillatory activity (Murphy, 2015, 2018, 2020; Benítez-Burraco and Murphy, 2019); one such mechanism that has been extensively studied is the interplay of gamma and theta oscillations. Several studies of this theta-gamma oscillatory coding mechanism have been conducted in rodents, monkeys, and humans, frequently involving the hippocampus and/or entorhinal cortex (Lisman and Idiart, 1995; Skaggs et al., 1996; Tort et al., 2009; Axmacher et al., 2010; Nyhus and Curran, 2010; Quilichini et al., 2010; Friese et al., 2013; Lisman and Jensen, 2013; Heusser et al., 2016; McLelland and VanRullen, 2016; Headley and Pare, 2017; Kikuchi et al., 2018; Zheng et al., 2022). Such studies have implicated the theta-gamma "code" in multi-item working memory (Lisman and Idiart, 1995; Axmacher et al., 2010), memory for navigating mazes (Skaggs et al., 1996; Quilichini et al., 2010), and the order of events in an episodic memory

Nyhus and Curran (2010); Heusser et al. (2016). While these represent the prototypical functions believed to be subserved by the hippocampus and entorhinal cortex, the theta-gamma code has also been implicated in sensory processing, including in olfactory processing in rats (Woolley and Timiras, 1965), and most important for the consideration of language, in processing of auditory stimuli in the primary auditory cortices of rhesus monkeys (Lakatos et al., 2005). A delta-theta-gamma cross-frequency coupling of oscillatory activity has been proposed as a potentially domain-general computation that could be implemented in language processing brain areas for the purpose of phrase building (Murphy, 2015, 2018, 2020; Benítez-Burraco and Murphy, 2019).

In the delta-theta-gamma "code" for phrase building proposed by Murphy (2015), Murphy (2018), Benítez-Burraco and Murphy (2019), and Murphy (2020), low frequency delta (0.5–4 Hz) activity modulates theta (4–8 Hz) activity, which in turn modulates neural activity occurring at higher frequencies in the gamma (>30 Hz) range, such that gamma wave activity is "embedded" within particular phases of a theta wave and theta wave activity is "embedded" within particular phases of a delta wave. Phonetic and phonological information has been suggested to be represented by a burst of neural activity occurring in a particular gamma frequency, and the relative ordering of those items within a lexical item is represented by the phase of the modulating theta activity that the gamma bursts occur in. In turn, the relative ordering of lexical items within a constituent is represented by the phase of the modulating delta activity which the theta activity occurs within.

The delta-theta-gamma oscillatory mechanism for phrase building proposed by Murphy (2015), Murphy (2018), Benítez-Burraco and Murphy (2019), and Murphy (2020) has good empirical evidence including from ECoG, MEG, and computational modeling studies (Ghitza, 2011; Giraud and Poeppel, 2012; Peelle and Davis, 2012; Ding et al., 2016; Martin and Doumas, 2017; Getz et al., 2018; Kaufeld et al., 2020; Lo et al., 2022). Rather than rehash this proposal, we wish to address the issue of "scope" in phrase building, i.e., how some lexical items in a phrase can combine before others. While this issue has received considerable attention in the literature, Rabagliati et al. (2017) provides insight of particular importance. Rabagliati et al. (2017) used a behavioral experiment showing reaction time differences for processing different types of one-, two-, and three-word phrases with different scope interpretations. Their results suggested that some types of three-word phrases are processed as quickly as two-word phrases, but more importantly, the time required to process a three-word phrase was related to its complexity and scopal interpretation. The types of two- and three-word phrases they suggest are processed the fastest are those that involve a simple structure and what Rabagliati et al. (2017) term "synchronous" activation; meanwhile, more complex phrases involve "asynchronous" or a combination of synchronous and asynchronous activation, where synchronous activation is used to combine some elements of a constituent prior to others. The synchronous activation strategy is reminiscent of the simultaneous and somewhat separate processing of shape and color information in visual processing, with some indication that synchronized activity between shape- and color-representing neural ensembles contributes to their perception as a unified whole (Milner, 1974; Hopfield and Brody, 2001; Romera et al., 2022, though this has been disputed, cf. Di Lollo (2012)). The theta-gamma code can encode information represented in this way through multiple simultaneously active gamma oscillations, in that neural ensembles active with the same gamma frequency and within the same period of the theta are represented together (Lisman and Jensen, 2013). As discussed above, the delta-theta-gamma code can be used to represent and integrate information processed in a serial manner—i.e., the asynchronous activation strategy described by Rabagliati et al. (2017).

Synthesizing the processing strategies of Rabagliati et al. (2017) with the delta-theta-gamma code, populations of neurons representing different lexical items which are combined using the synchronous strategy may oscillate at the same theta frequency and at the same phase of a modulating delta oscillation, with this synchronous activity serving to bind the items together conceptually and syntactically. Lexical items which are combined using the asynchronous strategy may oscillate at slightly different theta frequencies but crucially at different phases of the modulating delta frequency; constituents where lexical items are combined using both strategies can be represented by a combination of multiple lexical items active in the same phase of a delta cycle as well as different phases. Why might a particular set of words be processed using the synchronous strategy instead of the asynchronous one? One possibility is predictability: words that are highly predictable based on others may be preactivated via network effects during the same phase of the delta cycle as the prior word and with approximately the same theta frequency, potentially leading to a synchronization of activity. However, a robust discussion of the issue of preactivation in language processing is outside the scope of this paper. Nevertheless, that the theta-gamma code has indeed been implicated in predictive processing in other domains (Lisman and Jensen, 2013, for review). Another possibility is, as briefly discussed above, that the IFG reactivates lexical representations at an appropriate phase of the modulating delta cycle, such that multiple lexical representations are active simultaneously, leading to their conceptual combination.

A number of factors make the synchronous activation mechanism described above slightly less plausible though. In visual perception, shape and color information can activate neural populations tuned to their respective stimulus response characteristics simultaneously and in parallel; in auditory speech, only one word can be received at once. The situation is similar in sign language too, where, hypothetically, two signs that form a constituent could be produced simultaneously—yet we do not see this, they are still produced one after the other. Additional factors such as frequency of syntactic structure, pragmatic context, prior knowledge, etc. are also known to influence sentence processing and may require a more flexible representational mechanism than simultaneous activation of neural populations. A mechanism whereby parallel activation necessarily leads to a unified perception would further fail to account for psycholinguistic evidence that we build multiple syntactic parses in parallel.

3.5.3. Abstract representations: schemas and cognitive maps

Among linguists and psycholinguists there is considerable debate about whether syntactic information is stored in lexical entries or is mentally represented in more abstract constructions such as a TRANSITIVE CONSTRUCTION. With ample evidence on both sides, some indications are emerging that in fact both types of information are mentally stored and utilized (Tooley and Bock, 2014). How we synthesize these views and their associated findings however is an open question. A full synthesis of lexicalist and construction-based processing accounts awaits exciting new theoretical advancements, however it is worthwhile to consider how these two forms of representations may arise and are processed. Once again, we propose we can look to other cognitive domains for clues to organizational and processing principles that may carry over into the linguistic domain.

The first of such clues can come from visual processing. It is well-accepted that visual processing streams are organized hierarchically, where low-level features such as colors and the presence of light or darkness are processed early in visual processing streams, e.g., V1. Signals from V1 then feed further up the stream to V2, which processes edges from combinations of signals indicating light and dark. V2 itself feeds into regions that process shapes and movement, and so on. The further up this processing stream hierarchy, the more holistic and abstract the representations are. While a more direct parallel may come from processing the fine-grained auditory information of speech, a similar principle may be at play such that more "fine-grained" lexical information is stored and processed lower down language processing stream hierarchies, while more abstract constructions, such as the TRANSITIVE CONSTRUCTION, and conjunctions between lexical items are stored and processed further up the hierarchies. This principle may apply to both of the processing streams we propose here for entities and for events/scenes, with the ATL acting as an endpoint in the ventral stream where conjunctions of nouns and attributive adjectives are processed, and the AG acting as an endpoint in the dorsal stream where abstract argument structure is processed. In both instances, the STS, STG, and MTG represent and process information related to individual lexical items. In the remainder of this section, we will focus on the abstraction of argument structure information, as this is a particular point of contention between lexicalist and constructionist theories. The abstract construction representations we propose as being stored and processed in AG may be the result of abstraction over many instances of particular grammatical forms, or result from more semantically based scene schemas, or perhaps both. While we believe that both processes are at play, adjudicating which type of abstractions (purely syntactic or purely semantic) are represented awaits further study. Instead, we will speculate as to how these abstractions may emerge and interact.

We will first consider the semantically based scene schema abstractions. It is important that we define what we mean by "schema" before proceeding, as the term has been used in many different ways across the relevant literature. We define "schema" here in a similar vein as Gilboa and Marlatte (2017) and Reagh and Ranganath (2018), i.e., as abstract representations of scenes that serve as templates of a sort, built on commonalities between multiple prior experiences. For example, a schema for viewing a film may include the general event sequence of purchasing a ticket, buying concessions, finding a place to watch the film, and finally watching the film on a large screen located at the front. More specific details such as the layout of a particular cinema, whether one must find seats in a theater or a parking location at a drive-in, whether you prefer popcorn or candy, etc. are abstracted over. These schemas may be generated either via "gist" representations of scenes—which evidence suggests are encoded by a proposed posterior-medial (PM) network involving parahippocampal, and medial and ventrolateral parietal cortices, including the AG (Ranganath and Ritchey, 2012; Ritchey et al., 2015a,b; Inhoff and Ranganath, 2017; Reagh and Ranganath, 2018; O'Reilly et al., 2022)—or via abstraction over episodic scene representations—which evidence suggests involves both the aforementioned PM network in addition to a proposed anterior-temporal (AT) network involving perirhinal and ventral temporopolar cortices. Determining which of these proposed network accounts is correct awaits further study, but in either model the AG is an important component; the AG has also been implicated in visual processing of actions and scenes, in line with a proposed role for relational and spatial processing generally (Seghier, 2013; Gilboa and Marlatte, 2017; Fernandino et al., 2022). The type of information encoded in the model of visuospatial schemas adopted here has been suggested to provide the basis for schemas in other modalities such as time (Summerfield et al., 2020). For example, models of linear navigation through space have been suggested to generalize to neural representations of integer progression in counting and to representations of the progression of time. It should be noted that schemas are one particular event representation abstraction argued to be instantiated by the PM network, with other representations containing more specific details or being more structurally basic (Reagh and Ranganath, 2018). Notwithstanding the potential influence of event representations along a broad spectrum of abstractness, given the consistent findings of AG activation in processing phrases with action, event, or relational meaning, we can synthesize these data to suggest an at least partially semantic basis for verb argument structure representations using scene schemas.

Abstract syntactic representations could emerge in an analogous manner to abstractions over visual scenes, that is as abstractions over repeated instances of particular constructions (see also Hahn et al., 2022, for computational modeling evidence that similarly connects probabilistic syntactic parsing to visual processing). For example, repeatedly hearing a noun phrase followed by a verb and subsequently another noun phrase across various different lexical instantiations and contexts could abstract to a more general transitive construction. Such a process may rely on similar mechanisms as have been argued to generate schemas, by abstracting over repeated visual scenes and extracting the statistically common elements (Summerfield et al., 2020). The level of detail encoded in schemas is a matter of controversy, though it is perhaps likely that schemas at several levels along a detail-abstraction spectrum are represented, as has been argued to occur for syntactic constructions (Goldberg, 2003, 2013; Reagh and Ranganath, 2018; Summerfield et al., 2020) A tenable mechanism for instantiating such representations comes in the form of so-called "cognitive maps," a framework proposed to unify representations of spatial and non-spatial structural knowledge. Cognitive maps are argued to represent "states" and transitions between them in a structured but abstract manner, allowing for their flexible use across a variety of different contexts and potentially across sensory or processing domains as well (Behrens et al., 2018; Park et al., 2020; Boorman et al., 2021). Cognitive maps have been implicated as representational structures in several domains, including navigation, reward-based decision making, and tracking social hierarchies (Behrens et al., 2018; Park et al., 2020, 2021; Boorman et al., 2021). An important feature of cognitive maps relevant for their use in language as we are suggesting is their ability to represent latent hierarchical structure between states based only on statistical regularities between them—including inferring relationships between states that have not been directly observed (Behrens et al., 2018; Boorman et al., 2021). While this suggestion is more speculative, this feature could potentially allow for cognitive maps to represent the latent hierarchical structure between words and constituents within sentences. Moreover, the structure of these cognitive maps can be constrained by structure generated from sensory features (Behrens et al., 2018), hinting that the visual scene schemas described above could serve to constrain "maps" of the relationships between linguistic constituents in a sentence. Cognitive maps could also potentially be used to implement anaphoric reference: canonical place cells are selectively active when an animal is at a particular spatial location, while canonical grid cells are active when an animal is at any of several different locations (Behrens et al., 2018). In combination with cells coding particular referents (as analogues of place cells), "grid" cells in such a linguistic cognitive map may respond to multiple uses of referents by different methods (e.g., name vs. pronoun) across different linguistic contexts (e.g., different clauses).

3.5.4. Cortical organizational principles

The preceding sections have touched upon issues related to general principles of cortical organization that bear summarizing and synthesizing, namely, sensory processing hierarchies. Sensory processing proceeds from subcortical to primary sensory cortices, to secondary sensory cortices, to primary and secondary association cortical areas. The pathways between these are of course not strictly serial, with subcortical projections to secondary sensory cortices, feedback loops from higher cortical regions, etc.; however, they do reflect a general principle such that processing of very finely detailed sensory information, such as the wavelength of light or frequency of sounds, are processed early in the relevant sensory stream (and consequently very quickly). Cortical regions further up these streams process and encode conjunctions of lower-level information, creating abstractions over this more fine detail; association cortices, which include large portions of the temporal, parietal, and frontal lobes, can (though do not always) integrate information from multiple sensory domains. Such organization allows for information to be encoded at multiple levels of abstraction simultaneously. Psycho- and neurolinguistic research models have long proposed that phonological information and lemma information are both encoded separately and simultaneously, but whether even more abstract linguistic forms (e.g., constructions) are as well has been more controversial. However, the encoding of multiword constructions at multiple, simultaneous levels of specificity would be in keeping with these principles of hierarchical processing and the abstractions they afford. While temporal lobe association cortical areas may be more selective than parietal association regions, that both afford mechanisms for computing conjunctions and abstractions over sensory features suggests a distributed computation is responsible for such combinatorial operations.

4. Discussion

4.1. Tying it all together: a new dual stream model based on semantic divisions and its implications for theoretical syntax

To summarize our proposed model, we divide syntactic processing into two streams: a ventral stream dedicated to combinatorial processing of nominals and attributive adjectives, and a dorsal stream dedicated to combinatorial processing involving verbs and relational adjectives (Figure 1). For processing phrasal constituents, the ventral stream culminates in the ATL while the dorsal stream culminates in the AG; in constructing sentences, the two streams interact both directly through white matter tracts extending from the temporal lobe to the parietal, as well as indirectly through the IFG. Because the model we propose here separates phrasal processing into two streams, a mechanism that can be instantiated along both must be involved: the delta-theta-gamma oscillatory code, which is further used to communicate between the involved brain regions (Murphy, 2015, 2018, 2020; Benítez-Burraco and Murphy, 2019). Regions in the mid superior temporal cortex are used as indices of semantic role, which the IFG may take part in properly assigning, utilizing white matter tracts between the STC and IFG. The IFG may also play a role in generating the low-frequency oscillatory activity used across the language system, including by pSTS, the ATL, and AG for phrase building and long-distance communication (Murphy et al., 2022b).

The apparent selectivity for the ATL in processing nominal phrases reflects a bias toward multimodal integration, namely with vision (Tanenhaus et al., 1995). In order for our lexical items to have semantic content, we must associate them with objects in the real world (setting aside the issue of more abstract lexical items such as *ideas* or *dreams*). One method of doing this is to associate the auditory lexical signal of an object with a corresponding visual signal. Given that the ventral visual stream extends into the posterior temporal gyrus and appears to selectively process objects and object-relevant attribute information (size, shape, color, etc.) (Ishai et al., 1999; Giménez Amaya, 2000), then the ATL as a locus of associating nominal and attributive lexical items with visual object representations is quite logical. Moreover, the temporal lobe has demonstrated hierarchical organization for both visual and auditory stimuli, oriented along dorsal-ventral and anterior-posterior axes, in humans and other primates (Bao et al., 2020; Blazquez Freches et al., 2020; Braunsdorf et al., 2021; Sierpowska et al., 2022). Hierarchical processing of visual stimuli extends from primary visual cortex in the occipital lobe along ventral temporal cortex, with increasing conjunctions of features

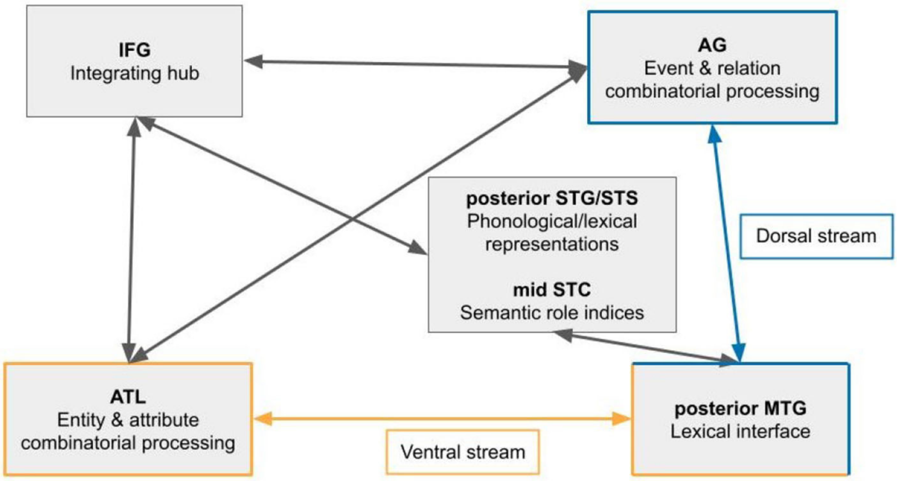

FIGURE 1
Proposed dual-stream model of syntactic combinatorial processing. The ventral stream is specialized for building phrases involving nouns and attributive adjectives; the dorsal stream is specialized for building phrases involving verbs and relational adjectives.

computed and invariance of representation extending anteriorly from primary visual cortex (Braunsdorf et al., 2021). Auditory processing extending from primary auditory cortex shows a similar hierarchy, but arranged in a more concentric circular pattern, with regions closer to A1 coding for low-level features such as frequency, tone, etc.; extending further outwards, lexical representations and socially important information such as speaker identity are coded (Braunsdorf et al., 2021). Importantly, the ATL as well as MTG appear to be regions of convergence for both auditory and visual processing, with some arguing that MTG dynamically codes for conjunctions of visual and information from other modalities (Weiner and Grill-Spector, 2013; Braunsdorf et al., 2021). A similar point will be returned to as we now shift our attention to the AG and its involvement in event semantics and verb argument structure processing.

Complementary to the ventral visual stream is the dorsal visual stream, extending from primary visual cortex to parietal cortex, which processes spatial and action information (Goodale and Milner, 1992; Orban et al., 2004). Once more, we must bind our lexical items to particular concrete instantiations (again leaving aside the issue of more abstract concepts); in this case of verbs, they must be associated with particular actions, events, or states. By a similar logic as that proposed for nouns being bound to visual representations in the temporal lobe, verbs can be bound to visual action representations in the parietal lobe. The richness with which object information is represented in comparison to more sparsely represented spatial information by the visual system appears to have a profound influence on language, confirming the importance of linking object/noun binding in the temporal lobe and action/verb, event/construction binding in the parietal lobe (Landau and Jackendoff, 1993). This is perhaps more true for spoken languages than signed languages such as ASL; given their primary reliance on a manual-visual modality, certain operations may be more biased toward reliance on parietal regions, particularly given the extensive multimodal nature of association cortical regions in the parietal lobe (Corina et al., 2013).

Of course, actions do not occur without other entities either performing them or being affected by them (or both), nor do they occur removed from a particular spatial context. As cortical locations that make up part of the "where" stream of visual processing, and by integrating object information from the ventral visual stream, the parietal lobe can represent relational information between entities (reviewed in Cloutman, 2013; Ray et al., 2020). The conjunction of action, spatial, relational, and object information constitute the essential elements of an event. How can we get from the event semantic representations that appear to be processed by the AG to more general argument structures though? To begin with, the confluence of multiple sensory inputs in the parietal lobe suggests some manner of abstraction over these, in order to build appropriate associations between them (Binder and Desai, 2011). The large amount of informational components of an event combined in the AG is no exception. Firstly, there is ample evidence that people make fine-grained distinctions about the semantics of an event based on changes in argument structure (Wittenberg, 2018, for review). For example, Wittenberg et al. (2017) provide eye tracking and behavioral data that suggest participants, who were implicitly trained to classify sentences based on the number of semantic roles, interpret light verb constructions (e.g., *give a kiss*) intermediately between three semantic role constructions (e.g., in the prototypical ditransitive *give* construction) and two semantic role constructions (e.g., a prototypical transitive construction like *kiss*). They take this as evidence that two sets of competing event semantics are being activated, one set from the light verb and the other from the nominalized action, suggesting that argument structure influences event construals. Moreover, Ramchand (2019) argues that constrained event representations track systematically with particular argument structures, and especially important, that generalizations of event semantics and generalization of syntactic argument structures go hand-in-hand. In particular, she argues that a constrained decomposition of events into their component parts maps consistently to syntactic argument structures—including embedded clauses as subevents.

This discussion also brings up a fundamental question of how we generalize to new linguistic input. Certainly semantics plays some role, but how do we know that in a sentence like *Nala glorped the dax to the flort*, *Nala* is likely somehow transferring *the dax* item to *the flort* entity or location? O'Reilly et al. (2022) argue that more abstract, and increasingly content-general representations can be learned in the parietal lobe through an error-driven process, where sensory input is compared to sensory predictions. An abstract syntactic construction may be an example of such a representation, with particular arrangements of slots that are open for different lexical items. What type of learning mechanism can be employed that allows for learning abstract construction information in an error-driven way? A Bayesian type learning algorithm could fit the bill. Although we are unaware of a study testing this hypothesis specifically, Perfors et al. (2010) is potentially indicative; the authors implemented a hierarchical Bayesian learning model to simulate how a language learner might successfully cluster verbs into two classes depending on whether they alternate between the double-object and preposition-object forms or not. Using information about distributional statistics alone, the model was able to learn how many classes of verbs existed, as well as correctly assigning particular verbs to each class. This model therefore suggests a mechanism for learners to acquire even more abstract patterns of verb constructions: based on a confluence of the syntactic environments verbs appear in, as well as the semantics of each lexical item and the semantics of the overall clause, a Bayesian learner could generalize clusters of verbs that occur with a single nominal phrase and share event semantics of a single entity performing an action, and so on for other constructions. Coupled with the Perfors et al. (2010) model, both an abstract construction, the distribution of constructions, and the set of verbs participating in each construction could be learned, such that encountering a sentence like *Nala glorped the dax to the flort* allows a Bayesian learner to hypothesize that: (1) *glorp* is part of the set of verbs that participate in the ditransitive construction; (2) that it therefore likely carries a meaning of transfer or one thing to another entity or place; and (3) that it is more likely to only occur in the prepositional object construction. With that said, Bayesian modeling has been critiqued as not a good approximation of how the brain operates at the neuronal level, and its approximation to higher-level cognition rests on the assumption that what happens at the neural level can mostly be ignored or abstracted away from (O'Reilly et al., 2012).

To get a more neurobiologically grounded understanding of how such event abstractions may occur (though not quite at the level of individual neurons), we return to the issue of schemas and cognitive maps. Again, we wish to emphasize that we are not making an argument based on a strongly embodied view of language, but instead one where sensory perceptions provide a semantic basis and constraint for linguistic structure. Abstraction over sensory perceptions of events to create event schemas or situation models may provide a meaning basis for particular grammatical constructions; for example, abstracting over many individual visual/somatosensory instances of someone handing an object to another person or animate entity may generate a "giving" or "transferral" schema consisting of an object being transferred from one entity to another. When coupled with a systematic and regular pairing of a particular grammatical form, these schemas provide a basic general template for meaning to be more fully fleshed out by the specific lexical items used and the entities they denote. The level of abstraction of schemas is a matter of debate within the literature, reflective of a similar debate in theoretical syntax between lexical and construction representations of argument structure. For example, more detailed situation models (as proposed by e.g., Reagh and Ranganath, 2018) could be viewed as similar to more detailed lexically-based argument structures, in that a more specific event may be denoted by both the situation model and a verb. Meanwhile, more abstract schemas (as proposed by e.g., Summerfield et al., 2020) could be viewed as similar to more abstract construction-based argument structures, in that both schemas and argument structure constructions represent very general knowledge about entities and their relative spatial locations and interactions. As in language, these are not necessarily irreconcilable, with potentially multiple levels of abstraction occurring and being simultaneously drawn upon. Abstract representations built upon commonalities between prior sensory experiences, like those proposed here, should result in "fuzzy" category representations, with some instances sharing more commonalities with core features of the category than others. This is an important aspect of linguistic categories that has been explored in Cognitive Grammar with respect to lexical semantics and syntactic structures. Despite the aforementioned critiques, iterative Bayesian algorithms may model these aspects of learning abstract categories quite well.

Models of cognitive schemas assign important roles for medial temporal lobe (MTL) structures (including the hippocampus, perirhinal cortex, entorhinal cortex, and parahippocampus) in forming these schemas; extending this model to language acquisition suggests a more active contribution for these brain regions than has been previously appreciated. Some important recent work has begun incorporating MTL structures into neurobiological models of language, providing productive space for further research (Piai et al., 2016; Murphy et al., 2022a) This model similarly implies a more critical contribution of the AG in language acquisition and in connecting linguistic and visual representations, given suggestions that parietal lobe regions act as amodal hubs for compressing the dimensional space of sensory representations (Summerfield et al., 2020; O'Reilly et al., 2022). This model of interaction between visual and linguistic representations can help explain a fairly strong consistency in argument structures cross-linguistically (Nichols, 2011). This is not to say that the interaction is unidirectional—linguistic structure may serve to orient or contain attention to specific objects or entities in a visual event. For example, using *give* in a ditransitive argument structure may help alert a language learner that there are three entities or objects to which they should pay particular attention in a given visual scene, and that they should ignore or pay less attention to extraneous entities/objects that were not mentioned linguistically. The interaction between visual representations, linguistic representations, and attention may further help to explain argument structure alternations (e.g., the double-object and prepositional-object alternation) and argument structure optionality (e.g., *eat* is optionally transitive, while *devor* is obligatorily transitive, and *dine* is intransitive), but awaits further study—however, some joint eye-tracking and language production data from Pitjantjatjara and Murrinhpatha, two languages spoken by Aboriginal Australians with relatively free word order, are suggestive of this (Nordlinger et al., 2020).

That event semantics are somewhat separable from syntactic form though does suggest potentially separable neural mechanisms for encoding this information, bringing us to perhaps the most speculative aspect of this paper—i.e., that the relationship between constituents may be represented as a type of cognitive map. We are unaware of any evidence suggesting that sentential structure may be represented in this manner; however, given separate evidence that hierarchical structure in language may be learned based on input statistics, and cognitive maps are a mechanism which can convert statistical relationships between stimuli into hierarchical representations, we pose this question as a hypothesis for future research. This question has both theoretical and experimental components: from a theoretical perspective, can sentential structure be represented in a way that is conducive to being encoded as cognitive maps; and from the experimental perspective, can we find evidence that sentential structure *is* encoded in such a manner (e.g., by showing characteristic hexagonal firing fields for linguistically sensitive populations of neurons, etc.). Both of these questions have ramifications for theoretical syntax, as cognitive maps may represent a plausible neural mechanism for encoding the hierarchical structure of language, as well as providing a new and possibly more flexible representational configuration than allowed for in some theories.

Turning now to the delta-theta-gamma code, the contribution of oscillatory brain activity to language processing has been investigated previously, and while the details are still being elucidated, a good deal of progress has been made in understanding the role cross-frequency coupling plays in language (Murphy, 2015, 2018, 2020; Benítez-Burraco and Murphy, 2019). Some of these studies have focused on frequencies within the delta range, reporting increases in power that appeared correlated to specific manipulations of linguistic stimuli at various levels still within the delta range—including increases in power at frequencies in the delta range linked to the formation of constituents (Getz et al., 2018; Lo et al., 2022). This data comes with a caveat, that reported increases in power at a particular frequency do not necessarily indicate an increase in oscillatory neural activity at that frequency, and may include transient ERP responses, line noise, and ocular and muscular activity artifacts (Barry and De Blasio, 2021; Donoghue et al., 2021; Keil et al., 2022). Nevertheless, the evidence of IFG activity tracking constituent size, delta frequencies tracking formation of constituents, and certain brain regions acting as indices of sorts for specific representations, coupled with other evidence of linking prefrontal cortical activity to oscillatory codes mediating communication between brain regions does suggest both a plausible role for the IFG (or at least portions of it) and oscillatory mechanisms in constituent building. Given that the IFG sits at the intersection of white matter tracts extending from both the temporal and parietal lobes, it may serve to bind together nominal constituents composed in the ATL and verbal constituents composed in the AG. How this information is ultimately bound together is an open question as well, though it could be accomplished as a computation the IFG itself performs, or by IFG coordinating oscillatory activity among these regions and the regions of mSTC suggested as indices of semantic role—either by generating the underlying delta frequency used in phrase building in other brain regions or by generating even lower frequency oscillations that modulate delta. The modulation of delta activity by even lower-frequency oscillatory activity has been suggested by Lakatos et al. (2005), though a modulatory role for the IFG would be in keeping with the functioning of other areas of prefrontal cortex in oscillatory codes (Heusser et al., 2016; Zheng et al., 2022).

Although the frequencies which have been previously proposed as making up the "code" for building constituent structures may not ultimately prove to be involved, we believe that such an oscillatory code is still a good candidate for representing this information (Murphy, 2015, 2018, 2020; Benítez-Burraco and Murphy, 2019). Such a code may afford more flexibility in its ability to represent online sentential information compared to other neural mechanisms for representing conjunctions of information, such as Hebbian plasticity, thereby capturing the productive nature of human language. Ultimately, several neural mechanisms are likely involved in the processes necessary to build a sentence from lexical items, but if a phase-amplitude coupling code is found to underlie constituent-building, better understanding its dynamics can provide theoretical insight on constraints of phrase structure building generally, including bearing on such issues as the infamous binary branching dispute, possible limitations on the number of lexical items encoded in a single constituent, and how discontinuous constituents are encoded and processed (see Murphy, 2020, for an extended discussion of these issues as they relate to oscillatory coding mechanisms). However, it is unclear how ordering rules would be instantiated in such a code, though this could potentially be accomplished using cognitive maps as we alluded to in Section 3.5.3. More work would also be needed to understand embedding in relation to oscillatory dynamics. Although the model of constituent-building we propose here is not lexicalist, that is not to say the influence of lexical information in syntactic structure building is nonexistent—instead it may proceed from the semantics of the lexical items providing constraints on possible structure (e.g., through schemas), or may be the result of interactions with other neural mechanisms such as cognitive maps or prediction fueled by Hebbian plasticity.

4.2. Unanswered questions

Due to the speculative nature of some sections of this paper, there are still many unanswered questions we have not addressed. One such question concerns the exact functional role of the IFG, which has long been implicated in syntactic processing. We suggest that it serves to communicate linguistic information across the language network, including by a correctly assigning semantic roles to constituents of a sentence, based on white matter tracts connecting it to the mid superior temporal cortical areas implicated as semantic indices (Frankland and Greene, 2015, 2019). This may account for its activation to sentences with non-canonical word order as well as the difficulties comprehending passive sentences shown by some patients with Broca's aphasia. Alternatively, or additionally, the IFG may serve to generate some of the oscillatory activity used by pSTS, the ATL, and AG to form constituents, given its increased activation as a function of comprehending increasingly larger constituents and increases in functional connectivity (Murphy et al., 2022b). We leave these questions, as well as questions about potential functional-anatomical divisions within the IFG to future work.

Another important unresolved issue is the function served by the posterior MTG. Here we have kept with previous models that have argued for pMTG as a hub for accessing lexical item representations, however some have also argued for a contribution to syntactic processing (Hagoort, 2013; Matchin and Hickok, 2020; Hickok, 2022). This interpretation is based on enhanced activation in pMTG for full sentences compared to word lists. pMTG further shows sensitivity to both words and pictures, suggesting its role in cross-modal integration of auditory and visual information (Visser et al., 2012; Braunsdorf et al., 2021; Murphy et al., 2022b).

In a similar vein, we have explored evidence for lateral and medial areas within the STS and STG acting as indices of semantic roles. While, as discussed above, we believe that this interpretation has merit in explaining certain comprehension difficulties for a subset of patients with Broca's aphasia, how this interpretation can be squared with the well accepted function of STS and STG in low-level auditory processing remains to be resolved. We would additionally be remiss not to discuss the ventromedial prefrontal cortex (vmPFC), which has been extensively implicated in the literature on cognitive maps as well as in some of the literature on syntactic processing (e.g., Allen et al., 2012). At present, this data is too inconclusive for us to draw a meaningful conclusion about the function of vmPFC, nor can we view this as evidence for the connection between syntax and cognitive maps we hypothesized in Section 3.5.3, especially given the wide variety of tasks vmPFC has also been linked to.

Many of these open questions of course highlight the limitations of neuroimaging techniques and the well-known reverse inference problem (Poldrack, 2006). Despite ourselves engaging in some amount of reverse inference, we are of the opinion that converging evidence using other methodologies and from other cognitive domains enhance the interpretations we offer here. These methodologies of course come with their own limitations that we must also acknowledge. With respect to the computational evidence we draw on, although these models attempt to simulate cognitive processes at the computational (or potentially the algorithmic) level, it is a leap to suggest that such results necessarily reflect actual cognitive or neural processes, rather than a best estimation based on our current understanding. In regards to the brief lesion and aphasiology data we draw on, it is important to note the highly interconnected nature of the brain, and therefore the strong probability for lesions to disrupt entire networks of functionality. Causally linking patients' symptoms to the loss of function incurred by the lesion alone must be done with extreme caution, lest the functions of multiple brain regions be subsumed under a single region instead. Finally, with regard to the ECoG data we examine, known limitations include the size, distribution, depth, and coverage of implanted electrode grids, as well as the fact that patients undergoing such experiments typically have severe epilepsy and the generalizability of results to the broader population must therefore be cautiously explored. Nevertheless, the interpretations here provide a new hypothesis space for further research that we hope will advance our understanding of the neurobiological basis of syntactic processing.

Author contributions

BG contributed to the conceptualization and wrote the first draft of the manuscript. DC was involved in conceptualization and supervision. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Dissociating the processing of empty categories in raising and control sentences: a self-paced reading study in Japanese

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Introduction: Theoretical linguistics has proposed different types of empty categories (ECs), i.e., unpronounced words with syntactic characteristics. ECs are a key to elucidating the computational system of syntax, algorithms of language processing, and their neural implementation. Here we examined the distinction between raising and control sentences in Japanese and whether ECs are psychologically real.

Methods: We recruited 254 native speakers of Japanese in the present internet-based experiment. We used a self-paced reading and a probe recognition priming technique. To investigate whether raising and control sentences have different ECs (i.e., Copy and PRO) and whether these ECs cause a reactivation effect, behavioral data were analyzed using linear mixed-effects models.

Results: We found two striking results. First, we demonstrate that the reading times of raising and control sentences in Japanese were better explained by the linear mixed-effects model considering the differences of ECs, i.e., Copy and PRO. Secondly, we found a significant reactivation effect for raising and control sentences, which have ECs, and reflexive sentences without ECs. These results indicate that ECs are processed similarly to reflexive pronouns (e.g., *himself*).

Discussion: Based on these results, we conclude that raising and control sentences in Japanese have different ECs, i.e., Copy and PRO, and that ECs have psychological reality. Our results demonstrate that behavioral experiment based on theoretical linguistics, which is the first step for developing linking hypotheses connecting theoretical linguistics and experimental neuroscience, is indeed necessary for testing hypotheses proposed in theoretical linguistics.

KEYWORDS

syntax, Japanese, self-paced reading (SPR), experimental linguistics, empty category, neurobiology of language, sentence comprehension, reading

Introduction

Theoretical linguistics has proposed different types of empty categories (ECs), i.e., unpronounced words, such as NP-trace (or Copy of a noun phrase) and PRO, each of which has different syntactic characteristics. The reason for incessant attention to ECs in generative syntax (Chomsky, 2021) is that ECs considerably reflect the basic mechanisms underlying linguistic computation. Compared to full nominal expressions such as *John*, ECs by themselves provide considerably few clues about their interpretation. Interpretation of ECs is only derived from syntactic, semantic, or pragmatic operations. Thus, the study of their interpretation provides us with a probe into the computational system of natural language (syntax) and ways to investigate the interfaces between syntax and other language systems (phonology, semantics, and pragmatics). Despite their importance in theoretical linguistics, behavioral and neural mechanisms of ECs are barely discussed in recent experimental linguistics (but see Makuuchi et al., 2013; Ohta et al., 2017; Tanaka et al., 2017 for notable exceptions). Behavioral and neural mechanisms of ECs are also critical for building linking hypotheses connecting theoretical linguistics and experimental neuroscience. Therefore, it is necessary to examine the property of ECs in detail, using experimental methods [e.g., self-paced reading (SPR)] and statistical analyses [e.g., linear mixed-effects (LME) models].

In the present study, as a first step to examine the behavioral and neural basis of ECs, we conducted an SPR experiment to elucidate the algorithms of language processing related to ECs. Behavioral experiments are crucial for discovering underlying algorithms of language processing, while neurophysiological experiments provide insights into the implementation of the algorithms in the brain (Marr, 1982; Krakauer et al., 2017). We especially focus on ECs of raising and control sentences in Japanese.

Raising and control sentences have been central concerns in theoretical linguistics, especially in generative syntax. A primary motivation for the attention on raising and control sentences is the similarity of the constructions in English, as shown in (1) and (2), which illustrate raising and control sentences, respectively.

(1) Barnett seemed to understand the formula. (Davies and Dubinsky, 2004).
(2) Barnett tried to understand the formula. (Davies and Dubinsky, 2004).

Both sentences have an intransitive matrix clause with an infinitival (non-finite) complement, NP-V-to-VP. The only surface difference is the matrix verb, *seem* vs. *try*. However, it has been pointed out that there are empirical differences between the two constructions since the early generative grammar (Chomsky, 1965, p. 22–24; Rosenbaum, 1967; see Landau, 2013 for review). In a raising sentence (1), the NP *Barnett*, which receives an agentive semantic role (θ-role) from an embedded non-finite predicate "*to understand the formula*", appears in a subject position of the matrix clause, suggesting that the NP has *raised* from the embedded clause to the matrix clause. Importantly, the original and ultimate positions are associated with a *single* argument. By contrast, in a control sentence (2), the NP *Barnett* appears to be associated with two θ-roles from both the matrix verb *tried* and embedded verb *understand*. While its syntactic position corresponds to the matrix θ-role, the interpretation of the sentence indicates that there is an additional argument in the embedded clause, which is coreferential with (or *controlled* by) the NP *Barnett*. Importantly, the two positions are associated with two arguments, which is similar to anaphora expressions (e.g., *myself*).

Raising and control predicates in this study are defined as follows. While both raising and control predicates take an infinitival complement clause, in which subject position is unpronounced, raising predicates assign a θ-role to an internal argument, whereas control predicates assign two θ-roles to an internal and external argument. In other words, the matrix subject of the raising sentence above (e.g., *Barnett*) is an Agent of the embedded verb *understand*, i.e., the person who understands the formula, but not an Agent of the matrix verb *seemed*. In contrast, the matrix subject of the control sentence is an Agent of both the matrix verb *tried*, i.e., the person who tried to do something, and the embedded verb *understand*. The number of θ-roles causes various different syntactic properties between raising and control sentences.

We will explain two representative differences between raising and control, which are observed both in English and Japanese control sentences. First, a feature distinguishing raising and control constructions is selectional restrictions to subject.

(3) The rock seems to be granite.
(4) # The rock tried to be granite.

(3) is a well-formed sentence, while (4) is semantically anomalous. The oddness in (4) results from the semantic requirements of *try*. The control verb *try* requires an agent subject, which needs an entity capable of volition. As the *rock* has no volition, (4) is a semantically odd sentence. Contrarily, the subject verb *seem* in (3) has no semantic sectional restrictions to subject. Thus, raising verbs allow non-animate subjects like *rock*.

Typical conditions in which Japanese raising and control structures appear are syntactic compound verbs. Similar to English, the surface string similarity and the functional differences between Japanese raising and control sentences have been widely reported (Kageyama, 1993; Koizumi, 1999, among others). For example, selectional restriction to subject was also reported in Japanese, as shown in (5) and (6).

(5) Ame-ga furi-*sugi*-ta.
Rain-NOM rain-too much-PST.
"It rained too much."

(6) * Ame-ga furi-*sokone*-ta.
Rain-NOM rain-fail-PST.
"It failed to rain."

The raising verb *sugi-ru* "do too much" allows non-animate subjects, such as *rain*, while the control verb *sokone-ru* "fail" requires the agent (or animate) subject.

Second, another difference is the behavior of idiomatic expressions.

(7) The cat is out of the bag. (Davies and Dubinsky, 2004).

The sentence in (7) has two meanings. One is a situation in which a particular cat is not in a particular container, and the other is that one-time secret is no longer a secret.

(8) The cat seemed to be out of the bag. (Davies and Dubinsky, 2004).
(9) ?The cat tried to be out of the bag. (Davies and Dubinsky, 2004).

With a raising predicate in (8), the expression can retain an idiomatic interpretation. However, with a control predicate in (9), the idiomatic interpretation is no longer possible.

The difference of idiomatic expressions is also reported in Japanese.

(10) Kankodori-ga nak-u.
Cuckoo-NOM sing.

(10) is a Japanese idiom, which has two interpretations. One describes a situation where a cuckoo sings, and the other

is that a store has hardly any customers. The latter is an idiomatic meaning.

(11) Kono mise-de-wa kankodori-ga naki-*kake*-ta.
This store-DAT-TOP cuckoo-NOM sing-almost-PST.
"A cuckoo almost sang in this store./This store almost closed down."

(12) Kono mise-de-wa kankodori-ga naki-*wasure*-ta.
This store-DAT-TOP cuckoo-NOM sing-forget-PST.
"A cuckoo forgot to sing in this store.

The raising verb *kake-ru* "almost" retains an idiomatic interpretation, while the control verb *wasure-ru* "forget" has no idiomatic interpretation. In addition, there are other empirical differences like θ-roles, passivization, scope ambiguity, and an expletive subject (Davies and Dubinsky, 2004; Landau, 2013).

From Chomsky (1973), referred to as "Extended Standard Theory", to Chomsky (1981), referred to as "Government and Binding Theory", it was established that raising and control sentences have different ECs, Copy (NP-Trace) and PRO as shown in (13) and (14). Chomsky (1981) defined that PRO has anaphoric and pronominal features, while Copy has only anaphoric feature.

(13) John$_i$ seems [Copy$_i$ to be a nice fellow.] (Chomsky, 1973, partially modified).
(14) John$_i$ expected [PRO$_i$ to win.] (Chomsky, 1973).

The syntactic properties of PRO have aroused intense debate within theoretical linguistics, because no full nominal expressions show anaphoric and pronominal features at the same time.

After the Minimalist Program Chomsky (1993), Hornstein (1999) proposed a new analysis to control the phenomena, which is called Movement Theory of Control (MTC). MTC primarily claims that obligatory control[1] is derived via *A-movement*. Thus, MTC considers that the null hypothesis for the derivation of raising and control sentences should resort to the same empty category, Copy. Hornstein's proposal has received crucial criticism (Culicover and Jackendoff, 2001; Landau, 2003; Bobaljik and Landau, 2009; Ndayiragije, 2012; Wood, 2012) and has provoked a great deal of controversy. Over the last few decades, the property of control sentences has been discussed and not settled yet in theoretical linguistics. To reveal whether control structures have PRO or Copy is important for advancing theoretical linguistics. If control had Copy, it would contribute to removing construction-specific category[2] and construction-specific module. Contrarily, if control had PRO, it would be useful for linguists to consider why PRO is construction specific. Thus, experimental linguistics is necessary to settle this issue.

ECs of control phenomena were widely studied using experimental approaches; however, these studies paid attention to the difference in behavior between *subject control* and *object control* (Sakamoto, 1996, 2001; Witzel and Witzel, 2011) and the process of *agreement* between PRO and its antecedent (Demestre et al., 1999; Betancort et al., 2004; Demestre and García-Albea, 2007). There are only few studies on the comparison between PRO and Copy.

Bever and McElree (1988), McElree and Bever (1989), Featherston et al. (2000), and Featherston (2001) studied the syntactic characteristics between PRO and Copy on sentence processing. Bever and McElree (1988) and McElree and Bever (1989) investigated various kinds of ECs in English. They used a *probe word recognition priming technique*, where a sentence is presented on a screen phrase-by-phrase. At the end of the sentence, a probe word appears on the screen. The participant must decide whether or not the probe word was contained in the presented sentence. They reported that sentences with ECs and pronouns showed significantly faster response times than sentences without ECs, which is called a reactivation effect. They also found that sentences that include Copy evoke significantly faster response times than control sentences that include PRO. Consequently, they claim that PRO should be distinguished from Copy. Featherston et al. (2000) employed ERP to examine the characteristics of ECs in German. It was reported that the comparison between raising and control conditions showed a significantly positive-going ERP for the former in the 600–1,000 ms time windows.

Featherston (2001) conducted a replication study of Bever and McElree (1988) using the SPR paradigm and probe word recognition task, in which English words were replaced by German words and the same conditions were used. However, the results were contrary to Bever and McElree (1988). There was no reactivation effect by ECs and no significant difference between PRO and Copy on the response times for recognizing the probe word.

Whether ECs are psychologically real or not is another controversial topic in experimental linguistics (Pickering and Barry, 1991; Gibson and Hickok, 1993). Bever and McElree (1988) and Miyamoto and Takahashi (2002) showed the evidence for the psychological reality of ECs by presenting the reactivation effect. However, Nakayama (1995) did not find a reactivation effect of ECs in Japanese. Nakano et al. (2002) also did not observe the reactivation effect of ECs in long-distance Japanese scrambling in a low reading span group. As mentioned above, Featherston (2001) also did not find the reactivation effect in German. Therefore, whether or not ECs show the reactivation effect remained unclear.

Although Bever and McElree (1988) and Featherston et al. (2000) contributed to revealing syntactic characteristics of ECs on human sentence processing, their studies are still unsatisfactory. The problem with previous studies is that they do not consider

1 Another angle to look at control phenomena was proposed by Williams (1980). He divided control into two categories: Obligatory control (OC) and non-obligatory control (NOC). The examples in (1) and (2) illustrate how these two categories differ.
OC
*It was expected PRO to shave himself.
NOC
It was believed that PRO shaving was important. (Hornstein, 2003).
For example, OC PRO needs an antecedent while NOC PRO does not.

2 It has been reported that PRO only appears in control constructions.

other factors that may influence the behavioral data and ERPs. As shown in Table 1, control and raising sentences have other differences along with the difference between PRO and Copy. There is a difference between raising and control structures in terms of the number of θ-roles. Second, Pesetsky (1991) reported another difference between raising and control structures regarding the types of θ-roles. Therefore, it is too early to conclude that the observed differences in previous studies were really derived from the difference of ECs. Furthermore, other general factors may influence outputs, as shown below.

> **Factors that affect behavioral data**: Word frequency, Number of characters, Number of morphemes, Clause types, Reactivation effect, and Spillover effect.

There are the frequency of words, number of characters, number of morphemes, clause types (e.g., Mono-clause vs. Bi-clause), reactivation effect, and a spillover effect, where a pre-critical region influences a critical region (Vasishth and Lewis, 2006; Nakatani, 2021). Featherston (2001) reported the opposite results to Bever and McElree (1988), which may reflect the differences of these general factors between English and German.

To solve the problems of previous experimental studies, we used Japanese raising and control sentences, which assign the same θ-role (Proposition). We further introduced causative sentences to control the number of θ-roles and reflexive sentences to control the reactivation effect. As an anaphora expression in the reflexive sentences (e.g., *myself*) takes an antecedent within a sentence, the reflexive sentences clearly cause the reactivation effect. In other words, we used the causative and reflexive sentences as positive control conditions. We further used a mono-clausal sentence without ECs as a baseline condition (i.e., a negative control condition).

We used linear mixed-effects (LME) models, which are effective to examine the influence of each factor on the behavioral data. LME models show how certain independent variables (e.g., frequency and clause type) affect a dependent variable (e.g., reading time for each region), including participants and sets of experimental sentences as random factors. To investigate whether control sentences have PRO or not, two models were created (Table 2, Hypothesis 1). In the first model, the control sentences have PRO and the raising sentences have Copy. In the second model, both the control and raising sentences have Copy. If PRO is to be distinguished from Copy, the former model should show better scores than the latter model. In other words, the former model will show a lower Akaike information criterion (AIC) than the latter model (Akaike, 1974). To further examine whether ECs cause the reactivation effect, two models were created (Table 2, Hypothesis 2). In the first model, the ECs and reflexive cause the reactivation effect. In the second model, only the reflexive causes the reactivation effect. If ECs also cause the reactivation effect, the former model should show lower AIC scores than the latter model. Regarding Hypothesis 2, our research interest was to examine whether ECs showed the reactivation effect, but not to test the difference of reactivation effect between PRO and Copy. Therefore, we did not distinguish Copy from PRO in our analyses. The control and raising sentences are critical for testing Hypothesis 1, while the raising, control, and reflexive sentences are crucial for testing Hypothesis 2.

Materials and methods

Participants

We recruited 254 self-reported native speakers of Japanese through Lancers (https://www.lancers.jp/), a crowdsourcing service in Japan. Following a data trimming procedure, which will be explained in Section 2.4, two participants were removed from the datasets. The final set included 252 participants (146 males) between the age of 20 and 71 years (mean = 42.82, s.d. = 9.72). We used a Latin-square design and divided target sentences into five lists. Following the previous SPR study (Witzel and Witzel, 2011), which included 48 participants, we recruited about 50 participants for each of the five stimulus lists, resulting in 254 participants.

Stimuli

In this experiment, we used five types of sentence materials (see Supplementary material for all materials). Spaces indicate region boundaries for the presentation. All conditions consisted of 6 regions, and PRO and Copy were not presented to the participants (Figure 1). Note that the stimuli, glosses (word-by-word translations), and their English translations are shown here with the Modified Hepburn Romanization system of Japanese, but actual stimuli were presented in a combination of "kanji" and "hiragana". Vowels with a macron (*ā*, *i*, *u*, *ē*, *o*) denote long vowels.

(15) a. Raising condition.
Nakamura$_i$-ga senshū kayōbi-ni [Copy$_i$ *kaisha-de Takahashi-o shikari*]*-sugi-ta*.
Nakamura-NOM last week Tuesday-DAT at an office Takahashi-ACC scold-too much-PST.
"Nakamura scolded Takahashi too much at an office last Tuesday."

b. Control condition.
Nakamura$_i$-ga senshū kayōbi-ni [PRO$_i$ *kaisha-de Takahashi-o shikari*]*-sobire-ta.*
Nakamura-NOM last week Tuesday-DAT at an office Takahashi-ACC scold-fail to-PST.
"Nakamura failed to scold Takahashi at an office last Tuesday."

c. Reflexive condition.
Nakamura-ga senshū kaisha-de jibunjishin-de Takahashi-o shikat-ta.
Nakamura-NOM last week at an office myself Takahashi-ACC scold-PST.
"Nakamura scolded Takahashi by himself/herself at an office last week."

d. Causative condition.
Nakamura-ga senshū [kaisha-de Yamashita-ni Takahashi-o shikar]-ase-ta.
Nakamura-NOM last week at an office Yamashita-DAT Takahashi-ACC scold-CAUSE-PST.

TABLE 1 Different factors among conditions.

Conditions	ECs	Number of morphemes	Number of θ-roles	Clause type	Reactivation effect
Raising	Copy	3	3	Bi-clausal	?
Control	PRO	3	4	Bi-clausal	?
Reflexive	NA	2	2	Mono-clausal	+
Causative	NA	3	4	Bi-clausal	–
Baseline	NA	2	2	Mono-clausal	–

Reflexive, Causative, and Baseline conditions did not contain ECs. The number of morphemes indicates the total number of morphemes in the (compound) verb. The number of θ-roles indicates the total number of θ-roles within a sentence. The reactivation effect under the Raising and Control conditions remained unclear. NA, Not applicable; +, Having the reactivation effect; –, No reactivation effect.

"Nakamura made Yamashita scold Takahashi at an office last week."

e. Baseline condition.
Nakamura-ga senshū kayōbi-ni kaisha-de Takahashi-o shikat-ta.
Nakamura-NOM last week Tuesday-DAT at an office Takahashi-ACC scold-PST.
"Nakamura scolded Takahashi at an office last Tuesday."

In addition to the conditions of interest, i.e., the Raising and Control conditions, we included three additional conditions to control the influence of dependent variables. First, we used the Reflexive condition to investigate the influence of the reactivation effect. As we mentioned in the Introduction, whether ECs cause a reactivation effect is not clear. However, anaphora expressions (e.g., *jibunjishin and myself*) in reflexive sentences clearly cause a reactivation effect. The Causative condition was used to examine the influence of the number of θ-roles. The causative morpheme in Japanese assigns "Agent" θ-role to an external argument, e.g., *Nakamura* (Shibatani, 1973), thus, it resulted in the same number of θ-roles with the Control condition. Theoretical linguistics has proposed that causative constructions in Japanese have bi-clausal sentence structures (Shibatani, 1973). Finally, the Baseline condition, which did not contain ECs and therefore did not cause reactivation effect, was used as a baseline for the sentence that may cause reactivation effect (Raising, Control, and Reflexive conditions).

While the types of θ-roles are different between raising and control sentences in English (Pesetsky, 1991), both raising and control constructions assign the same θ-role, i.e., "Proposition", to an internal argument in Japanese (Kageyama, 2016). Therefore, we can control the difference between the θ-role types in the present study.

This experiment used 150 (30 × 5) target sentences and 150 filler sentences. The filler sentences had similar sentence construction to the target sentences, and they also had six regions. All the target sentences and half of the filler sentences were followed by the probe word. Following Bever and McElree (1988) and Featherston (2001), the sentence-initial noun phrase served as the probe word in the target sentences. To prevent the participants from anticipating the probe position, we set the probe word in different regions of the filler sentences. The other half of the filler sentences were followed by a "yes/no" comprehension task; for instance, "It was Yamashita that Takahashi scolded last Tuesday." for (15d). All the human-related proper and common noun phrases consist of two characters and four morae in Japanese.

TABLE 2 Hypotheses, models, and prediction.

Hypothesis 1:	PRO is distinguished from Copy
Model (PRO + Copy):	Control has PRO and raising has Copy.
Model (Copy + Copy):	Both control and raising have Copy.
Prediction:	Model (PRO + Copy) will show lower AIC.
Hypothesis 2:	**ECs cause the reactivation effect**
Model (ECs + reflexive):	ECs and reflexive cause the reactivation effect (i.e., shorter probe word recognition time).
Model (reflexive):	Only reflexive causes the reactivation effect (i.e., shorter probe word recognition time).
Prediction:	Model (ECs + reflexive) will show lower AIC.

Procedures

The experiment was run on PCIbex (https://doc.pcibex.net/), an online linguistic experiment hosting service (Zehr and Schwarz, 2018). Before the main experiment, participants read the instructions and received a maximum of three practice sessions. Each session consisted of five practice trials. Only participants who answered four or more trials correctly in any sessions were moved to the main experiment. For example, when a certain participant could answer four trials correctly in the first session, the second and third practice sessions were skipped. If a certain participant failed to get four or more scores in any session, the participant was refused to participate in the experiment. The experiment took ∼15–20 min, including the time to read the instructions and the practice parts. As compensation, JPY 120 was paid to each participant.

In this experiment, we used a non-cumulative moving window SPR paradigm and the *probe word recognition priming technique*. A total of 30 × 5 target sentences were distributed into five lists using a Latin-square design. Thirty filler items were added to each list. A total of 60 sentences shuffled in a pseudo-random order, with

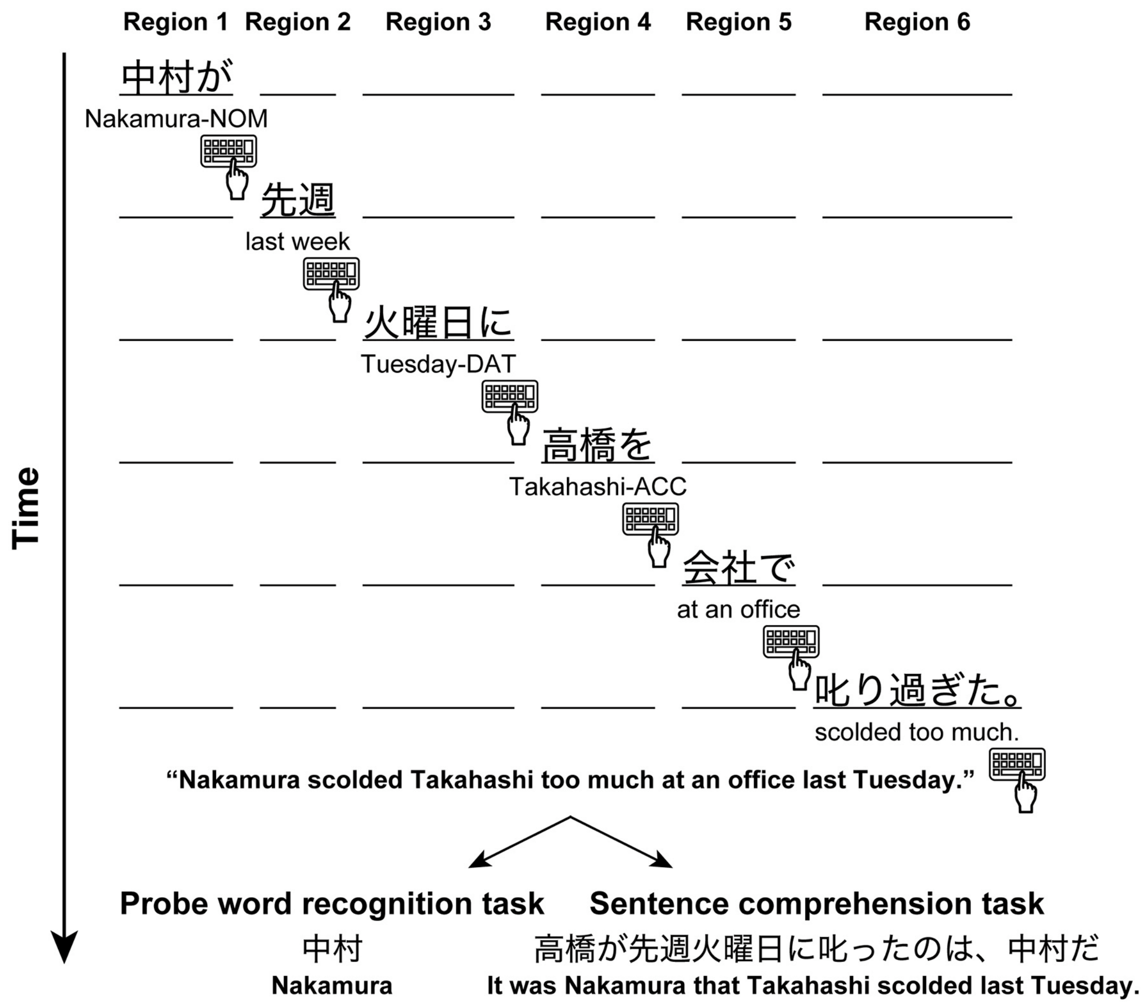

FIGURE 1
Self-paced reading (SPR) paradigm. Every sentence stimulus consisted of six phrases without showing ECs, brackets, or hyphens. Each sentence began with a "+" mark to signal where the sentence started. After that, each sentence initially appeared as a series of underbars, with each underbar corresponding to each region of the sentence. Each region appeared on a screen when the participants pressed the space bar. After the space bar was pressed for the last region, the participant either received the probe word or the comprehension question. All the target sentences and half of the filler sentences were followed by the probe word. The sentence-initial noun phrase served as the probe word in the target sentences. To prevent the participants from anticipating the probe position, we set the probe word in different regions of the filler sentences. The other half of the filler sentences were followed by a "yes/no" comprehension task. For the examples of the probe word recognition task in this figure, the participants had to answer "yes", while for the example of the sentence comprehension task, they had to answer "no".

no more than three targets or three fillers, can be presented in a row. After every 20 items, the participants were encouraged to take a short rest. Each sentence began with a "+" mark to signal where the sentence started. After that, each sentence initially appeared as a series of dashes, with each dash corresponding to each region of the sentence (Figure 1). When the space bar was pressed, each region showed up on a screen. The participant continued in this manner until the end of the sentence. After the space bar press for the last region, the item was removed from the screen. Then, the participant either received the probe word or the comprehension question. The probe word and the comprehension question were enclosed by two angles. If the probe word was presented, the participant answered "included" with the "F" key on the keyboard or "not included" with the "J" key. If the comprehension question was presented, the participant answered "yes" with the "F" key on the keyboard or "no" with the "J" key.

Data analysis

Following Witzel and Witzel (2011), data trimming was conducted in the following way. The data from participants (a) with error rates of 30% or greater on the target and filler sentences or (b) with error rates of 30% or greater on the target sentences were eliminated from the analysis. The data set of one participant was excluded based on these cut-off scores. For the probe word recognition task, the data that were answered incorrectly were eliminated from further analysis. Thus, 4.51% of the data were eliminated in this way. We also excluded trials including the reading time data or the probe word recognition time data longer than 4 s. The data set of 1 participant was excluded based on this procedure. Thus, 4.68% of the data were eliminated in this way. The outlier reading time data for each region and the recognition time data for the probe word were then trimmed as follows: the data that were two standard deviations above or below a subject's mean for a given region or task were replaced with the value two standard deviations above or below the participants' mean for that region or task. Thus, 4.74% of the data were trimmed in this way.

As for statistical analyses, reading and response time data were converted into natural logarithms. This study aims to compare the ECs of raising and control structures. The property of ECs was decided only when participants read Region 6 (verb position); that is, the raising and control structures from Regions 1 to 5 had no differences. Thus, our regions of interest were Region 6 and the following probe word recognition time. To confirm whether the behavioral data show the main effect of condition (Raising, Control, Reflexive, Causative, and Baseline), we conducted one-way repeated-measures analyses of variance (rANOVAs) for each region, the probe word recognition time, and accuracy. We used the "anovakun" function (version 4.8.7, http://riseki.php.xdomain.jp/index.php?ANOVA%E5%90%9B) in R (version 4.2.1). For *post-hoc* comparisons among the conditions, we applied Shaffer's modified sequentially rejective Bonferroni procedure.

For the above reason, LME models were only fitted for Region 6 and the probe word recognition time, using the *lmerTest* package in R (Kuznetsova et al., 2017). Note that all conditions were included in the following LME analyses. We first created the most complicated models that included all the factors that may affect the behavioral data as a fixed effect (i.e., the number of θ-roles, characters, morpheme, clause types, reactivation effect, and spillover effect) as shown in (16) (see also Introduction and Table 1).

(16) Complex Model < − lmer (Region 6/Probe word recognition time ∼ Frequency + Number of characters + Number of θ-roles + Number of morphemes + Reactivation effect + Spillover effect + Clause type + (1|Participant) + (1|Item), data = Data).

The detailed description of each dependent variable is the following. First, the frequencies of words were collected through the Balanced Corpus of Contemporary Written Japanese (https://chunagon.ninjal.ac.jp/ver. *Chunagon* 2.7.0) (Maekawa et al., 2013). Second, the number of characters and the number of morphemes were based on the (compound) verbs (Region 6) (Table 1). Third, the number of θ-roles was collected from the entire sentence (Raising = 3, Control = 4, Reflexive = 2, Causative = 4, and Baseline = 2). Fourth, we assumed Raising, Control, and Reflexive conditions cause the reactivation effect (these three conditions were assigned the dummy argument 1, and the other two conditions were assigned the dummy argument 0). We also included the logarithmic time of the pre-critical region as a fixed effect (spillover effect). Finally, we assumed raising, control, and causative structures are bi-clausal, and the others are mono-clausal (Raising, Control, and Causative conditions are assigned the dummy argument 1, and the others were assigned the dummy argument 0). Finally, the factor of θ-role types was not included as a fixed effect, because both control and raising constructions assign the same θ-role (2.2 Stimuli).

Both the participants' and items' intercepts were included in the model as random factors (Baayen et al., 2008). We also attempted to include random slopes as well, but we were forced to simplify the random effects until convergence failure and singularity warnings disappeared. Eventually, it was impossible to include random slopes.

We excluded irrelevant factors in Region 6 and the probe word recognition task by using the *step* function in the *lmerTest* package, resulting in the following fixed and random effects. To select significant factors, we used a stepwise backward elimination method widely used in the model selection of the LME analyses (Baayen, 2008; Matuschek et al., 2017).

(17) Region 6 ∼ Number of characters + Spillover effect (reading times of Region 5) + (1|Participant) + (1|Item).

(18) Probe word recognition time ∼ Spillover effect (reading times of Region 6) + Reactivation effect + Number of morphemes + (1|Participant) + (1|Item).

We fitted the number of characters and spillover effect as fixed effects, which showed significant effects, and added the ECs for the reading time of Region 6, as shown in (19) and (20). It should be noted that the variables of interest in our study were PRO, Copy, Reactivation, and Reflexive, thus, we included these factors without applying the stepwise variable selection in the following analyses.

We assigned the different dummy arguments for the Raising and Control conditions for the model (PRO + Copy) (PRO: Raising condition has dummy argument 1 and the others have dummy argument 0; Copy: Control condition has dummy argument 1 and the others have dummy argument 0). On the other hand, we used the same dummy argument for the Raising and Control conditions for the model (Copy + Copy) (Raising and Control conditions have dummy argument 1, and the others have dummy argument 0).

(19) Model (PRO + Copy) < − lmer (Region 6 ∼ Number of characters + Spillover effect + PRO + Copy + (1|Participant) + (1|Item), data = Data).

(20) Model (Copy + Copy) < − lmer (Region 6 ∼ Number of characters + Spillover effect + Copy + (1|Participant) + (1|Item), data = Data).

We also fitted the reactivation effect, spillover effect, and the number of morphemes as fixed effects and added the ECs for the reaction time of probe word recognition task, as shown in (21) and (22). Same as in the above models (19) and (20), we assigned the different dummy arguments for the model (PRO + Copy) and the same dummy argument for the model (Copy + Copy).

(21) Model (PRO + Copy) < − lmer (Probe word recognition time ∼ Spillover effect + Reactivation effect + Number of morphemes + PRO + Copy + (1|Participant) + (1|Item), data = Data).

(22) Model (Copy + Copy) < − lmer (Probe word recognition time ∼ Spillover effect + Reactivation effect + Number of morphemes + Copy + (1|Participant) + (1|Item), data = Data).

We also fitted the spillover effect and number of morphemes as a fixed effect for the reaction time of probe word recognition task, as shown in (23) and (24), to reveal the reactivation effect of ECs. We created two models. One was the model which assumed ECs and Reflexive conditions caused the reactivation effect (Raising, Control, and Reflexive conditions have dummy argument 1, and the other conditions have dummy argument 0). The other was the model which assumed only the Reflexive condition caused the reactivation effect (Reflexive condition has dummy argument 1, and the other conditions have dummy argument 0).

(23) Model (ECs + Reflexive) < − lmer (Probe word recognition time ∼ Spillover effect + Number of morphemes + Reactivation + (1|Participant) + (1|Item), data = Data).
(24) Model (Reflexive) < − lmer (Probe word recognition time ∼ Spillover effect + Number of morphemes + Reflexive + (1|Participant) + (1|Item), data = Data).

Previous studies reported reduced replicability of the results when selecting variables based on their statistical significance (Henderson and Denison, 1989; Mundry and Nunn, 2009). To check whether or not the variable selection caused any problems, we also tested the LME models including all variables hypothesized to be relevant, i.e., models without applying the stepwise variable selection. In the LME analyses comparing PRO and Copy, we could not include the number of θ-roles and the number of morphemes simultaneously due to the convergence failure. Thus, we created two models: One included all the variables except the number of morphemes, while the other included all the variables except the number of θ-roles. In addition, we included all variables without convergence failure when comparing the model that ECs and reflexive cause the reactivation effect with the model that only reflexive causes the reactivation effect.

Results

The main effect of condition

Mean of the raw reading times for each region and the probe word recognition times are summarized in Figure 2. The detailed results of the probe word recognition times are shown in Figure 3A. For Regions 1–5, there was no significant main effect of condition [Region 1: $F_{(4,\,988)} = 0.14$, $p = 0.97$; Region 2: $F_{(4,\,988)} = 0.21$, $p = 0.93$; Region 3: $F_{(4,\,988)} = 0.28$, $p = 0.89$; Region 4: $F_{(4,\,988)} = 2.1$, $p = 0.081$; Region 5: $F_{(4,\,988)} = 1.8$, $p = 0.14$]. For Region 6, we found a significant effect of condition [$F_{(4,\,988)} = 9.4$, $p < 0.0001$]. *Post-hoc* comparisons showed that the reading times of the Control condition were significantly longer than those of the Baseline, Causative, and Reflexive conditions [vs. Baseline: $t_{(247)} = 5.4$, corrected $p < 0.0001$; vs. Causative: $t_{(247)} = 3.3$, corrected $p = 0.0061$; vs. Reflexive: $t_{(247)} = 4.1$, corrected $p = 0.0003$]. In addition, the Raising condition also showed significantly longer reading times than the Baseline and Reflexive conditions [vs. Baseline: $t_{(247)} = 4.8$, corrected $p < 0.0001$; vs. Reflexive: $t_{(247)} = 4.6$, corrected $p < 0.0001$]. These results suggested that the Raising and Control conditions were more demanding. For the probe word recognition time, the effect of condition was also significant [$F_{(4,\,988)} = 13$, $p < 0.0001$]. *Post-hoc* comparisons showed that the probe word recognition time of the Causative condition was significantly longer than other conditions [vs. Raising: $t_{(247)} = 4.4$, corrected $p = 0.0001$; vs. Control: $t_{(247)} = 4.2$, corrected $p = 0.0002$; vs. Reflexive: $t_{(247)} = 6.0$, corrected $p < 0.0001$; vs. Baseline: $t_{(247)} = 5.3$, corrected $p < 0.0001$]. These results indicate that the difference of the sentence conditions changed the processing loads for the probe word recognition task.

The mean accuracy under every condition was higher than 95%, indicating the participants' reliable and consistent judgments on the task (Figure 3B). Furthermore, the rANOVA on the accuracy showed that the effect of condition was not significant [$F_{(4,\,988)} = 0.55$, $p = 0.70$], further suggesting that the task difficulty was controlled among conditions.

Comparison of PRO and Copy

To investigate whether control and raising sentences have PRO and Copy, respectively, we compared two models, i.e., models (PRO + Copy) and (Copy + Copy), for Region 6 (verb position) (Table 3). The model that hypothesizes PRO is distinguished from Copy showed a lower AIC score[3], suggesting that the participants processed PRO and Copy differently. The summary of the results from the best-fitting model (PRO + Copy) is shown in Table 3. The main effects were found in the number of characters factor and spillover factor, as well. The LME models including all relevant variables, i.e., models without applying the stepwise variable selection, showed similar results (Supplementary Tables S1, S2).

The result of model comparison for the probe word recognition times is presented in Table 4. Contrary to the previous result, the model hypothesizing that PRO is *not* distinguished from Copy showed a lower AIC score. The summary of the results from the best-fitting model (Copy + Copy) is also shown in Table 4. The main effects were found in the spillover effect, the number of morphemes, and Copy. The LME models without applying the stepwise variable selection also showed similar results (Supplementary Tables S3, S4). The number of morphemes was not significant in this model, while the number of characters was significant, reflecting a positive correlation between these variables.

Reactivation effect with ECs

To further examine whether ECs cause the reactivation effect, we compared two models, i.e., models (ECs + Reflexive) and (Reflexive), for the probe word recognition times. The result of model comparison for the probe word recognition times is presented in Table 5. The model which hypothesizes that both ECs and the Reflexive cause the reactivation effect showed a lower AIC score, suggesting the psychological reality of ECs. The summary of the results from the best-fitting model (ECs + Reflexive) is also shown in Table 5. The main effects were found in the spillover effect, reactivation effect, and number of morphemes. The LME models without applying the stepwise variable selection also

3 We compared models using Akaike information criterion (AIC), which is a measure of model quality that is based on the log likelihood and number of parameters of the model.

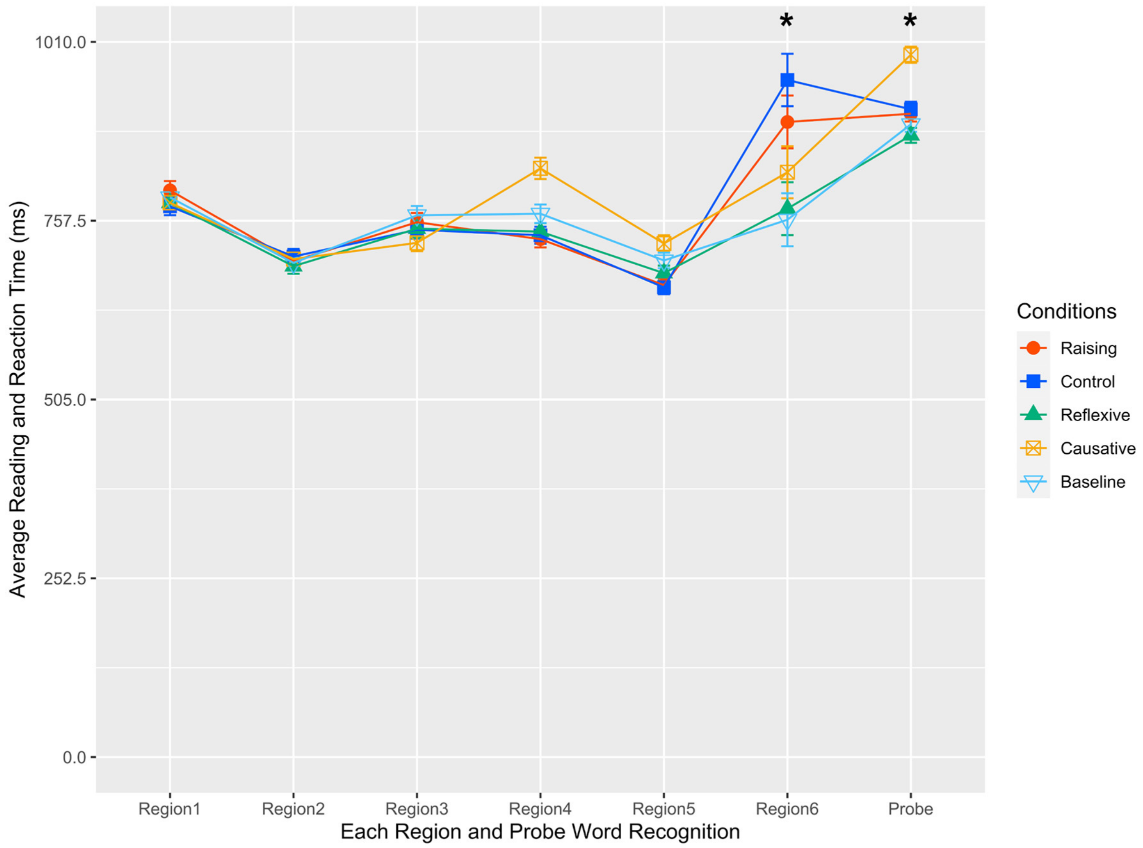

FIGURE 2
Average reading times and probe word recognition times. Error bars represent the standard error of the mean (SEM). *Corrected $p < 0.05$.

showed similar results (Supplementary Table S5). In this model, the number of morphemes was not significant, while the number of characters was significant, reflecting a positive correlation between these variables.

Discussion

In the present study, we investigated behavioral data of raising and control sentences, using the SPR paradigm and the *probe word recognition priming technique* with LME models (Figure 1), which shows how certain independent factors affect the behavioral output (Tables 1, 2). We found two striking results. First, we demonstrate that the reading times of raising and control sentences in Japanese were better explained by the LME model considering the differences of ECs (Figure 2; Table 3), suggesting the psychological reality of PRO and Copy. Secondly, we found a significant reactivation effect for raising and control sentences, which have ECs, and reflexive sentences without ECs (Table 5). These results indicate that ECs are processed similarly to reflexive pronouns (e.g., *himself/herself*). Based on these results, we conclude that raising and control sentences in Japanese have different ECs, i.e., Copy and PRO, and that ECs have psychological reality. Our results demonstrate that behavioral experiment based on theoretical linguistics, which is the first step for developing linking hypotheses that meaningfully relate neural circuits to syntactic processing (Krakauer et al., 2017), is indeed necessary for testing hypotheses proposed in theoretical linguistics. A more formulated hypothesis that compares raising and control structures is needed for further studies.

Previous experimental studies contributed to revealing syntactic characteristics of ECs on human sentence processing, but their studies are still unsatisfactory. The problem with previous studies is that they do not consider other factors that may influence the behavioral data and ERP. As shown in Table 1, control and raising sentences have other differences along with the difference between PRO and Copy. First, control predicates assign two θ-roles to an internal and external argument. Contrarily, raising predicates assign only one θ-role to an internal argument. There is a difference between raising and control structures in terms of the number of θ-roles. Second, Pesetsky (1991) reported that many control predicates assign "Irrealis" to an internal argument, but raising predicates assign "Proposition" to an internal argument. There is another difference between raising and control structures in terms of the types of θ-roles. Therefore, it is too early to conclude that the observed differences in previous studies were really derived from the difference of ECs. To solve the problems of previous experimental studies, LME models were used to show how certain independent variables affect a dependent variable and Japanese stimuli were used because of the same θ-role to an internal argument.

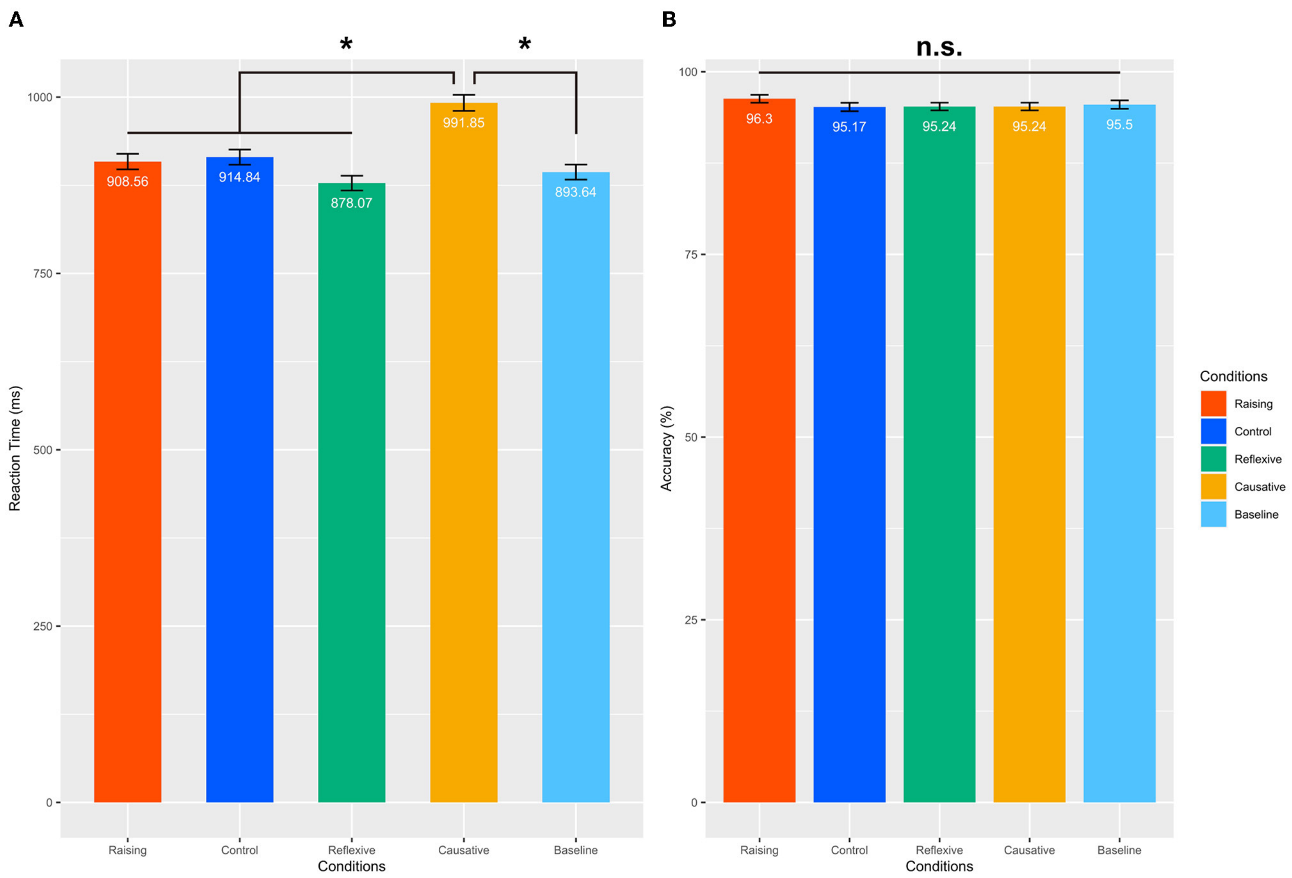

FIGURE 3
Probe word recognition times **(A)** and accuracy **(B)**. Error bars represent the standard error of the mean (SEM). *Corrected $p < 0.05$, n.s., not significant.

TABLE 3 Model comparison (ECs) and results of the LME models for Region 6.

Models	No. parameters	AIC	Log likelihood	Deviance	χ^2	*df*	*p*
Model (PRO + Copy)	8	5,539.1	−2,761.6	5,523.1	4.85	1	0.028
Model (Copy + Copy)	7	5,542.0	−2,764.0	5,528.0	0.146	1	0.70

Model (PRO + Copy)	Estimate	SE	*t*-value	*df*	*p*
(Intercept)	4.2	0.10	39.7	1,990	<0.0001
Number of characters	0.072	0.013	5.40	138.1	<0.0001
Spillover effect	0.32	0.014	22.8	6,851	<0.0001
PRO	0.043	0.038	1.15	138.1	0.25
Copy	−0.036	0.042	−0.863	136.9	0.39

As shown in Figure 3B, the results of rANOVA showed no significant difference on Regions 1–5 and the accuracy. As our regions of interest were Region 6 and the probe word recognition time, we investigated them in detail, using LME models. We found that the number of characters and the reading time of the pre-region strongly affect the reading time (Table 3). Furthermore, the spillover effect, number of morphemes, and Copy firmly influenced the probe word recognition time (Tables 4, 5).

Moreover, there is a significant difference between raising and control constructions in the SPR paradigm, as shown in Figure 2 and Table 3. These results support the theory that distinguishes between PRO and Copy. However, Figure 3A and Table 4 seemingly show the opposite result, which may support MTC. It is worth noting that the SPR and the probe word recognition task might reflect different mental processes. Online sentence processing may be strongly reflected in the SPR paradigm. Furthermore, a memory retrieval process may be reflected in the probe word recognition

TABLE 4 Model comparison (ECs) and results of the LME models for the probe word recognition task.

Models	No. parameters	AIC	Log likelihood	Deviance	χ^2	*df*	*p*
Model (PRO + Copy)	9	1,507.2	−744.6	1,489.2	0.115	1	0.74
Model (Copy + Copy)	8	1,505.3	−744.7	1,489.3	5.04	1	0.025
Model (Copy + Copy)	**Estimate**	**SEM**	***t*-value**		***df***		***p***
(Intercept)	5.7	0.095	60.7		309.7		<0.0001
Spillover effect	0.12	0.0085	14.3		6,105		<0.0001
Number of morphemes	0.10	0.030	3.45		139.1		0.0007
Reactivation effect	−0.031	0.030	−1.02		138.2		0.31
Copy	−0.089	0.040	−2.24		138.7		0.027

TABLE 5 Model comparison (reactivation effect) and results of the LME model for the probe word recognition task.

Models	No. parameters	AIC	Log likelihood	Deviance	χ^2	*df*	*p*
Model (ECs + reflexive)	7	1,508.4	−747.2	1,494.4	19.6	2	<0.0001
Model (reflexive)	7	1,523.4	−754.7	1,509.4	0	0	N/A
Model (ECs + reflexive)	**Estimate**	**SEM**	***t*-value**		***df***		***p***
(Intercept)	5.9	0.076	77.6		561.2		<0.0001
Spillover effect	0.12	0.0085	14.3		6,107		<0.0001
Reactivation effect	−0.081	0.020	−4.07		140.0		<0.0001
Number of morphemes	0.053	0.020	2.65		140.6		0.0090

task. These results do not contain inconsistencies and might merely reflect different mental procedures.

From the results shown in Figure 2 and Table 3, it is natural to conclude that PRO is distinguished from Copy. The behavioral data of the probe word recognition task showed no difference between raising and control sentences; however, it is very likely that neural processes will show the difference as reported in Featherston et al. (2000). Contrastingly, it is unnatural to hypothesize that the different, or contrary, behaviors are derived from the same neural process.

Although MTC has theoretically attractive points, it has many descriptive and theoretical problems. MTC is motivated to eliminate construction-specific PRO and module. Until the Government and Binding Theory, control phenomena were analyzed regarding a construction-specific grammatical primitive, PRO and a construction-specific interpretive system, the control module. Hornstein's analysis was supported in English and other languages (Boeckx and Hornstein, 2006; Fujii, 2006; Takano, 2010). However, Hornstein's proposal has received crucial criticism (Culicover and Jackendoff, 2001; Landau, 2003; Bobaljik and Landau, 2009; Ndayiragije, 2012; Wood, 2012). One of the descriptive problems is how to distinguish the differences of behavior of raising and control sentences, which are explained by the different ECs, i.e., PRO and Copy. For example, Takano (2000) pointed out that cleft sentences can be derived from control constructions, but cannot be derived from raising constructions as shown in (25) and (26). In Hornstein's analysis, it is difficult to explain this difference.

(25) It was [PRO to be frank] that John tried. (Takano, 2000).

(26) *It was [John to be frank] that John seemed. (Takano, 2000, partially modified).

In addition, Hornstein's analysis faces a theoretical issue that deals with adjunct control. Since Ross (1967), the prohibition of extracting from an adjunct is known as adjunct island. Therefore, a simple *A-movement* cannot be applied to adjunct control. To solve this problem, Hornstein (2000) proposed that the operation Copy and Merge should be allowed to apply freely between Workspaces, yielding *Sideward movement*. However, the *Sideward movement* has been widely criticized by researchers (Landau, 2003, 2007), because it over-generates non-existing ungrammatical sentences. In short, Hornstein's proposal faced the descriptive and theoretical issues. Thus, the conclusion of our study is recognized as appropriate in generative syntax.

Our study also indicated that ECs cause the reactivation effect and have psychological reality (Table 5). This conclusion is appropriate, especially in theoretical linguistics. It has been proposed that ECs have no phonetic features, but have the same syntactic features as pronounced constituents.

Bever and McElree (1988) found that sentences with Copy evoked significantly faster response times than control sentences with PRO. However, Featherston (2001), who conducted a replication study of Bever and McElree (1988) using German sentences, reported no significant differences between PRO and Copy on the probe word recognition times, which were the same as ours. Therefore, we assumed these controversial results were derived from word order differences. English takes SVO order in a complement clause, while both Japanese and German take SOV order in a complement clause.

Regarding the reactivation effect, Bever and McElree (1988) also reported that sentences with ECs and pronouns showed significantly faster response times than sentences without ECs. However, Featherston (2001) reported that sentences with ECs and pronouns did not show significantly faster probe word recognition times than those without ECs. Our results also showed no significant differences between the Raising, Control, and Reflexive conditions, which may cause the reactivation effect, and the Baseline condition on the probe word recognition times. We assumed that the difference in the word order could also explain these different results. English takes SVO order, while the Baseline conditions of our study and Featherston's study used SOV order. Therefore, the information of the object was active in English sentences because of SVO order and caused a stronger intervention effect in a memory retrieval process than in the Japanese and German studies. Contrarily, the information of the object was less active in Japanese and German because of the SOV order, which caused a weaker intervention effect.

As explained in the Introduction, we expected that the reactivation effect was related to the Raising, Control, and Reflexive conditions (see also Tables 1, 2). The results of LME models for the probe word recognition task demonstrated that the model that assumed the reactivation effect for the above three conditions was better than the model that assumed the reactivation effect for the Reflexive condition alone (Tables 5; Supplementary Table S5), which supported our Hypothesis 2. Moreover, the estimate of the reactivation effect was negative, further indicating that the probe word recognition times became shorter under these conditions. On the other hand, *post-hoc* comparison between the Reflexive and Baseline conditions was not significant. This result may seem odd because the Reflexive condition included a reflexive pronoun, which referred to the probe word, predicting shorter probe word recognition time than the Baseline condition. However, we think a simple mono-clausal construction of the Reflexive condition, which may cause a floor effect, can explain this result. Featherston (2001) also reported similar results, that is, mono-clausal sentences caused faster probe word recognition times than bi-clausal sentences. Moreover, the numbers of morphemes and θ-roles were smaller in the Reflexive condition than in the Raising and Control conditions (Table 1). Furthermore, the reading times of the pre-critical region (Region 6) under the Reflexive condition were shorter than those of the Raising and Control conditions (Figure 2), which may decrease the spillover effect. These factors were also related to the floor effect and reduced the reactivation effect in the Reflexive condition.

We also tested the LME models without applying the stepwise variable selection method (Supplementary Tables S1–S5). The models in which PRO was distinguished from Copy showed lower AIC scores in Region 6 (Supplementary Tables S1, S2). Moreover, the models in which PRO was *not* distinguished from Copy also showed lower AIC scores in the probe word recognition task (Supplementary Tables S3, S4). Finally, the models where both ECs and reflexive caused the reactivation effect showed lower AIC scores in the probe word recognition task (Supplementary Table S5). Taken together, these LME models supported the same conclusion as the models applying the stepwise variable selection methods.

To further investigate the neural processes of ECs, it is necessary to conduct experimental studies using neuroimaging techniques, such as ERP and fMRI. In the early years of experimental research, especially event-related potential (ERP) research, researchers focused primarily on syntactic (Neville et al., 1991; Osterhout and Holcomb, 1992; Friederici et al., 1993) and semantic (Kutas and Hillyard, 1980) violations and their electric indices, the LAN, N400, and P600. Moreover, neuroimaging studies using functional magnetic resonance imaging (fMRI) also focused on the neural basis of syntax (Dapretto and Bookheimer, 1999; Embick et al., 2000; Hashimoto and Sakai, 2002; Friederici et al., 2003; Musso et al., 2003). Recent fMRI studies have further examined the neural basis of a fundamental syntactic operation of human language, *Merge*, i.e., a simple and primitive combinatory operation that takes n syntactic objects and forms an unordered set of the syntactic objects (Chomsky, 1995). For instance, we demonstrated that the number of recursive applications of Merge accounted for syntax-selective activations in the left inferior frontal gyrus (L. IFG) (Ohta et al., 2013b; Tanaka et al., 2019; see also Ohta et al., 2013a for review). Other fMRI studies also reported that the L. IFG is crucial for the Merge operation (Zaccarella and Friederici, 2015; Zaccarella et al., 2017; Wu et al., 2019; Trettenbrein et al., 2021). Moreover, a growing body of work uses computational models to predict neural activity during sentence comprehension or production (Brennan et al., 2016; Hale, 2016; Li and Hale, 2019; Oseki and Marantz, 2020). For example, Brennan et al. (2016) reported that the number of nodes predicted the time course of participants' fMRI BOLD signal while they were listening to a natural story. In addition, neurostimulation techniques, such as transcranial electrical stimulation and transcranial magnetic stimulation, are also necessary to reveal causal relationships between language processing and neural activation. Furthermore, other types of control sentences proposed in theoretical linguistics, such as NOC, Adjunct control, and split control, should be examined in future studies.

Conclusion

To investigate the differences between raising and control sentences and whether or not ECs are psychologically real, we used the non-cumulative moving window SPR paradigm and the probe word recognition priming technique. As a result, we found that (1) raising and control sentences in Japanese have different ECs, i.e., Copy and PRO, and that (2) ECs cause the reactivation effect and they have psychological reality.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Board of Kyushu University, Faculty of Humanities. The patients/participants provided their written informed consent to participate in this study.

Author contributions

KY wrote the first draft of the manuscript. All authors contributed to conception and design of the study, prepared the task materials, performed the statistical analysis, contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The author SO declared that he was an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/flang.2023.1138749/full#supplementary-material

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Lexico-semantics obscures lexical syntax

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Introduction

A recently emerging generalization about language and the brain is that brain regions implicated in language that show syntax-related activations (e.g., increased activation for more complex sentence structures) also tend to show word-related activations, such as increased activation for reading real words (e.g., *poet*) relative to pseudowords (e.g., *tevill*). Fedorenko et al. (2020) generalize as follows: "...syntactic/combinatorial processing is not separable from lexico-semantic processing at the level of brain regions-or even voxel subsets-within the language network". Based on this generalization, Fedorenko et al. have made the conclusion..." that a cognitive architecture whereby *syntactic processing is not separable from the processing of individual word meanings* is most likely," arguing against "syntax-centric" views of language as promulgated by Chomsky and others. However, the notion of "lexico-semantics", a commonly used concept in the field of neurolinguistics, obscures the fact that words are both syntactic and semantic entities. Because of this, any functional neuroimaging experiment that manipulates lexicality will almost assuredly tax both syntactic and semantic resources and is therefore inadequate for isolating conceptual-semantic processing in the brain in addition to syntax. Unlike these sorts of neuroimaging studies, robust lesion data show clear functional-anatomical dissociations within the language network. Finally, a "syntax-centric" view of language is perfectly compatible with the state of the art in neurobiology because of the multiple potential mappings between linguistic theory and neurobiology beyond the level of individual brain regions. The present work presents a critique of Fedorenko et al. (2020) as a way to explore these more general issues.

Words and Rules

> *The way language works, then, is that each person's brain contains a lexicon of words and the concepts they stand for (a mental dictionary) and a set of rules that combine the words to convey relationships among concepts (a mental grammar) (Pinker, 1995).*

Pinker's work had a major impact in popularizing the ideas of Chomsky and mainstream generative grammar (MGG). Like Chomsky, Pinker forcibly argued for the concept of an innate linguistic module of the human brain that allows us to learn language. However, his work included some simplifications that have become ensconced in cognitive science. A major one was "Words and Rules" (Pinker, 1999; Pinker and Ullman, 2002): the idea that language is fundamentally two diametrically opposed systems, a database of form-meaning pairs (the lexicon) and a rule-based, combinatorial system (syntax), each rooted in distinct underlying brain systems (Figure 1, left). Pinker combined the traditional Saussurean notion of human language as fundamentally a system of arbitrary form-meaning pairs with the focus of generative grammar on combinatorial syntactic operations.

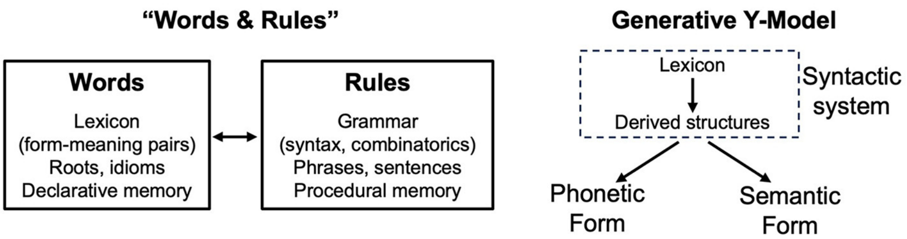

FIGURE 1
LEFT: the Words and Rules theory of Pinker (1999), adapted from Pinker and Ullman (2002). Separate cognitive systems are posited, each with distinct memory mechanisms, one containing a lexicon of form-meaning pairs (words) and one involved in combining lexical elements to create complex structures and semantic relations (rules). **RIGHT:** the Y-model posited in mainstream generative grammar (e.g., Chomsky, 1965, 1981, 1995b). A syntactic module, which combines lexical elements into complex structures, is then interpreted by two separate modules, one for phonetic form (how an expression is pronounced) and one for semantic form (the meaning of an utterance). In the Y-model, there is only an indirect and loose connection between the lexicon and meaning, whereas in the Words and Rules model, the lexicon is a repository of form-meaning pairs.

While many have taken the Words and Rules theory of Pinker to accurately summarize the MGG approach, these approaches are actually fundamentally incompatible (see also Embick and Marantz, 2005). The first models of MGG did not even contain a lexicon (Chomsky, 1955, 1957). Later models understood words as *syntactic* objects, inputs to syntactic computation, only later acquiring phonological and semantic expression (the inverted Y-model; Chomsky, 1965, 1981, 1995b) (Figure 1, right). Even further, Chomsky (1995a) proposed the theory of bare phrase structure, in which the labels of phrasal projections are not traditional syntactic categories like nouns and verbs but are rather derived from the lexical items themselves. For example, instead of verb phrases, there are "eat phrases"; instead of noun phrases, there are "cat phrases"; and so on. Some researchers have pointed to compelling evidence that words do not bear a direct mapping to meaning as Saussure claimed (Pietroski, 2018; Preminger, 2021), referring to phenomenon such as polysemy, in which the meaning of the same lexical item, for example, "book," is determined by syntactic context (e.g., *the book's pages were torn*—a physical object, *the book has challenged millions of readers to reexamine their views*—an abstract collection of words).

I do not claim that this approach is incontrovertibly correct. However, almost every modern (psycho)linguistic approach acknowledges that words have syntax, a point not raised or addressed by Fedorenko et al. (2020). The most popular alternative approach to MGG, the construction grammar/usage-based approach (Jackendoff, 2002; Goldberg, 2003), while advocating for a clearly distinct approach to language, does not abolish the distinction between syntax and semantics but, rather, articulates that words and constructions are *pairs* of syntactic form and meaning. In addition, popular psycholinguistic models of word production involve two stages: the first stage involves going from meaning to the lemma, which includes the syntactic representation of a concept; the second stage includes going from the lemma to the phonological form (Kempen and Huijbers, 1983; Levelt, 1989; Dell and O'Seaghdha, 1992; Levelt et al., 1999).[1] The idea that word retrieval involves access to syntactic information, even in the context of single-word production, is mostly uncontroversial in this literature. Thus, the idea of a coherent lexico-semantic system entirely distinct from and diametrically opposed to syntax is, in many ways, an aberration, yet it appears to have had a substantial impact on cognitive neuroscience.[2]

Functional differentiation in the language network

Fedorenko et al.'s claims about the neurobiological implementation of language are unusually strong and are based on the problematic notion of "lexico-semantics" reviewed earlier. First, Fedorenko et al. (2020) argue against the idea of a purely syntactic system in the brain because several previous studies "found that any language-responsive brain region or electrode that shows sensitivity to syntactic structure... is at least as sensitive, and often more sensitive, to meanings of individual words." This is simply the observation that regions implicated in syntax activate more to real words than pseudowords;[3,4] there is no evidence that these activations only reflect *meaning*. A syntactic system in the brain should activate more to real words relative to pseudowords, reflecting access to syntactic elements as reviewed earlier. Thus, the "lexico-semantic" activations reported in these experiments are ambiguous between lexical-syntactic and lexical-semantic processing.

Then, Fedorenko et al. (2020) performed a series of three additional functional magnetic resonance imaging experiments

1 Some have critiqued the notion of lemmas (Krauska, 2023). However, the alternative view of speech production articulated by these authors also involves two steps with an intermediate syntactic layer.

2 Many researchers use the term *lexico-semantic* to refer to a conglomeration of lexical and conceptual processing that excludes syntax. However, there is an alternative, viable usage of *lexico-semantic* that refers to monadic concepts.

3 The term *non-word* should be supplanted by *pseudo-word*. It acknowledges the complexities of the potential higher level linguistic processing that occurs when people process them (Vitevitch and Luce, 1999).

4 In many of these experiments, the word lists include morphologically complex forms and morphosyntactic features such as past tense. Thus, syntax is often present in the putatively "lexico-semantic" conditions.

designed to separately target "lexico-semantic" and syntactic processing, following similar experimental designs in previous research (Dapretto and Bookheimer, 1999; Kuperberg et al., 2000, 2003; Friederici, 2003; Noppeney and Price, 2004; Menenti et al., 2011; Segaert et al., 2012). This article provides example stimuli from the critical, putatively "lexico-semantic" conditions in Fedorenko et al. (2020). In these experiments, the initial sentence or clause is followed up by a second sentence or clause that contrasts with the initial one:

Experiment 1: "Although his ears were damaged... the man could still cook" (meaning violation)
Experiment 2: "The protestor quoted the leader -> The striker cited the chief" (different words)
Experiment 3: "The scientist flattered David -> The scientist misled David" (non-synonym)

All three of these experiments conflate syntax and semantics within the "lexico-semantic" condition. In Experiment 1, the meaning violation is also a violation of the expected word, which is a syntactic, as well as a semantic, element. In addition, it is quite possible that violations of meaning are accompanied by syntactic revision processes in order to attempt to reinterpret the sentence. In Experiment 2, different words are different syntactic elements, as well as different meanings. In Experiment 3, the manipulation involves changing the final word, which is again both a syntactic and a semantic element. It is, therefore, no surprise that brain areas thought to be potentially selective to syntax (such as the inferior frontal lobe and posterior temporal lobe as postulated by many authors; Hagoort, 2005; Tyler and Marslen-Wilson, 2008; Bornkessel-Schlesewsky and Schlesewsky, 2013; Friederici, 2017; Matchin and Hickok, 2020) show activations to both the "lexico-semantic" and syntactic conditions because the"lexico-semantic" conditions always involve a "hidden" syntactic manipulation. That is, these experiments always manipulate words, which are intrinsically syntactic as well as semantic, which is a consensus position in linguistic theory as reviewed earlier.

Researchers using similar experimental conditions in brain imaging research have reported dissociations of syntactic and semantic processing (Dapretto and Bookheimer, 1999; Kuperberg et al., 2000, 2003; Friederici, 2003; Noppeney and Price, 2004; Menenti et al., 2011; Segaert et al., 2012), which seem to be discrepant with the results reported by Fedorenko et al. (2020). However, these previous authors reported whole-brain activation maps, whereas Fedorenko et al. do not. It is possible that the subtle spatial dissociations reported by previous authors would be replicated in the Fedorenko et al. experiments if whole-brain analyses had been reported.[5] Regardless, it is more important that these previous authors operated under the same mistaken assumption as Fedorenko et al.: that "lexico-semantic" manipulations do not tax syntax. The fact that Fedorenko et al. do not (appear to) replicate the syntax–semantics dissociations reported by previous authors is more likely due to the fact that these original experimental designs were flawed to begin with.

Future functional neuroimaging studies investigating the syntax–semantics distinction should account for the dual semantic and syntactic nature of the lexicon by eschewing the conventional notion of "lexical-semantics" itself. Instead, researchers should develop more careful experiments that independently vary the richness of conceptual-semantic content and lexical-syntactic complexity or separately model these components during sentence comprehension (see Pylkkänen, 2019, 2020 for reviews; Hale et al., 2022).

Syntax in the brain: multiple viable instantiations

Fedorenko et al. (2020) focus on the idea of a syntactic system in the brain that should *not* be activated by lexical manipulations, a prediction that does not follow from "syntax-centric" theories of MGG (e.g., Chomsky, 1965, 1981, 1995b). However, they do report a significant preference for the syntactic condition in the posterior temporal lobe for Experiment 2 when using a localizer more sensitive to syntax. It is not a coincidence that the posterior temporal lobe has been strongly implicated in syntax by recent authors (Bornkessel-Schlesewsky and Schlesewsky, 2013; Pylkkänen, 2019; Matchin and Hickok, 2020). Recent lesion-symptom mapping literature supports a strong association between syntactic comprehension deficits and damage to posterior temporal-parietal areas (Pillay et al., 2017; Rogalsky et al., 2018; Matchin et al., 2022a,b), a similar pattern that is also emerging for paragrammatic speech production deficits (Yagata et al., 2017; Matchin et al., 2020). Residual functional activation in the posterior temporal lobe after accounting for lesion effects appears to be uniquely associated with aphasia recovery (Schneck, 2022; Wilson et al., 2022). Given that lesion-symptom mapping provides a much stronger causal inference than functional neuroimaging (Rorden and Karnath, 2004), such data need to be addressed together.

Finally, while I find the evidence for a hierarchical, abstract syntactic system in the posterior temporal lobe to be highly compelling, a variety of multiple perspectives on this issue are possible. First, even if no brain region is selective for syntax, specific network configurations could be (Schnitzler and Gross, 2005; Buzsaki, 2006; Anderson, 2016; Farahani et al., 2019). Furthermore, linguistic theories do not make predictions about how much cortical surface area would be needed to process syntax and semantics or whether there must be large cortical areas dedicated to processing syntax at all (Poeppel and Embick, 2005; Embick and Poeppel, 2015). The ideas of Chomsky regarding the uniqueness and expressive power of syntax are perfectly compatible with a "slight rewiring of the brain" (Chomsky, 2005) of an evolutionarily recent hominin ancestor, augmenting a sea of brain mechanisms that resulted in the modern human language faculty (Berwick and Chomsky, 2016), regardless of whether there is clear evidence of a large swath of syntax-selective cortex.

Author contributions

WM conceived and wrote the entire article.

5 In many papers, Fedorenko et al. do not report whole-brain analyses. However, they are critical supplements to region of interest analyses, potentially revealing hidden patterns in the data and allowing for better comparability across studies.

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Defying syntactic preservation in Alzheimer's disease: what type of impairment predicts syntactic change in dementia (if it does) and why?

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Introduction: Many studies on syntax in dementia suggest that, despite syntactic simplification, speakers with Alzheimer's disease (AD) retain their basic grammatical abilities, being mainly affected in their comprehension and production of complex syntax. Moreover, there is no single position on the origin of syntactic decline in AD, which, according to some authors, can be linked to a lexical-semantic deficit or, according to others, to either cognitive or autonomous dysfunction.

Methods: In this study, we apply the model of syntactic maturity to the analysis of oral speech production elicited by the Cookie-Theft description task. We assess a sample of 60 older adults (21 HC, 19 MCI, and 20 AD) through three indexes of syntactic maturity, measuring the proportion of sentences and clauses in discourse, their mean length, and the rate of their complexity.

Results: Our results show two important tendencies in AD: the preservation of general syntactic ability, as measured by the basic syntactic organization of speech, and the disturbance of the indexes of syntactic complexity, as measured by the overall length of utterances and their indexes of complexity.

Discussion: Although speakers with AD maintain the ability to construct grammatically acceptable sentences and produce a similar number of utterances to healthy aging speakers and speakers with MCI, the syntactic complexity of their discourse significantly changes. Importantly, such significant changes are already present at the MCI stage and are not conditioned by the lexical-semantic deficit itself. Our results may be particularly relevant to improving the detection of cognitive impairment and to theoretically discussing the relationships between language levels in aging speakers.

KEYWORDS
syntactic ability, Alzheimer's disease, aging, lexical-semantic deficit, cognitive impairment, syntactic complexity

1. Introduction

1.1. Syntax in aging and Alzheimer's disease

General preservation of syntactic ability is considered one of the hallmarks of language profile in dementia. One of the pioneering papers on changes in syntax in Alzheimer's disease (AD) found that, despite simplification of key features of syntactic complexity, speakers with dementia still produced coherent and grammatical sentences (Kemper et al., 1993). As the most frequent type of spontaneous dementia, AD is generally assumed to lead to significant disruptions in lexical semantics (Forbes-McKay and Venneri, 2005; Taler and Phillips, 2008; Verma and Howard, 2012; Lofgren and Hinzen, 2022) and phonetics (De Looze et al., 2018; Vincze et al., 2021; Ivanova et al., 2022). However, equally pronounced changes in syntax are not usually reported. Available results mainly suggest simplification, rather than significant impairment of syntactic ability in AD. This is a major challenge since, as opposed to language structures and phenomena allowing for qualitative differentiation of AD in a more targeted way (Alzheimer, 1907; in Alzheimer et al., 1991), syntactic change implies defining the level of impairment on a continuum.

Indeed, many studies show that while progression to dementia decreases the ability to produce complex utterances, such utterances remain grammatically acceptable and correct even in the moderate stage of AD. Syntactic simplification in AD would usually affect the length and the internal structure of utterances. Speakers with AD produce shorter utterances and clauses and use fewer propositions, verbal forms, and conjunctions (Kemper et al., 1993). The internal structure of their utterances is based on shorter mean dependency distances (Liu et al., 2021) and includes fewer embedded clauses (Bose et al., 2021). AD speakers use fewer coordinated and reduced structures (abbreviated subordinate clauses) (De Lira et al., 2011), fewer subordinate sentences (Croisile et al., 1996), and more sentential fragments than full sentences (Lyons et al., 1994). In some cases, AD speakers are reported to exhibit difficulties for passives (Bates et al., 1995).

At the same time, AD speakers match healthy aging speakers in formal grammatical correction and well-formation (Lyons et al., 1994). AD speakers can use recursive sentence embedding (Bánréti et al., 2016) or even sophisticated utterances (Mueller et al., 2016) like healthy elderly. Furthermore, their utterances are defined by a similar type-token ratio (Chapin et al., 2022). Importantly, despite all changes, utterances produced by AD speakers are generally informative enough, though the number of information units (that is, units of reference they might speak about) is usually reduced (Kemper et al., 1993; Croisile et al., 1996).

One intriguing question is how we can explain both the preservation (although partial) and changes in syntax in AD, and, particularly, how we can identify which of such changes are differentiating and relevant linguistic features of cognitive and language patterns of dementia. Speakers with AD rely on different, compensatory mechanisms in their cognitive and language performance. Yet, some of their syntactic features are similar to those observed in healthy aging. Indeed, some works suggest that syntax in AD bears a resemblance to some patterns of syntactic change in healthy aging. In their seminal study, Kemper et al. (2001) observed that speakers with dementia showed a similar pattern of decline in grammatical complexity (although not in the pattern of decline in propositional content) that healthy aging speakers. The authors concluded that even speakers with advanced dementia could still produce grammatical sentences. At the same time, some syntactic features change significantly in AD and can be considered a critical behavior marker of dementia progression. In fact, the processing of passives has been described as such critical behavior marker of Mild Cognitive Impairment (Sung et al., 2020). Although the manifestation of syntactic changes is more pronounced in the advanced stages of dementia (Ahmed et al., 2013), changes are significant in both the parts of speech and the syntactic structures themselves (Liu et al., 2021).

Such results on syntax in AD can be partially explained by our evidence on syntax during the lifespan and, specifically, in healthy aging. Syntactic competence is generally robust across the lifespan after its scalar development during childhood. Older adults usually preserve syntax in spite of aging-related neurocognitive changes. Despite aging-driven atrophy, gray-matter reduction, and decreased between-network connectivity in the brain, the syntactic ability is supported in older adults by neurofunctional reorganization and general functional preservation of the frontotemporal syntax system (cf. Tyler et al., 2010; Campbell et al., 2016). Furthermore, the preservation of syntax in aging is supported by the high level of automatization of the processes of integration of syntactic and semantic properties in sentential representations (Campbell et al., 2016). Neurobiological insights into the aging brain suggest that aging as a process conveys a general decline in the integrity of the left frontotemporal syntactic network, but there is no evidence for dedifferentiation of the syntactic system and, thus, for the reduction in its functional specialization (Shafro and Tyler, 2014). It is, therefore, not surprising that aged speakers recur to syntactic structures similarly to how young speakers do it, although they find it more difficult to adapt to contextual changes in syntactic patterns (e.g., when there is a shift from passive to active structures) (Heyselaar et al., 2021). Evidence from AD suggests that speakers with dementia also preserve their general syntactic competence, specifically if it is compared with other language domains, like lexical semantics or phonetics. Only fine-grained analyses, and only analyses conducted for advanced stages of AD, would suggest difficulties and/or impairments in processing syntactically constrained or ambiguous sentences (cf. Bickel et al., 2000).

Our contention is that an adequate approach to considering syntactic changes in AD must consider another, albeit related, point of ambiguity for syntax in dementia: its etiological background. The two possible positions are the lexical-semantic origin and the cognitive origin.

On the one hand, syntactic changes in healthy aging can be related to the difficulty in lexical access. Despite the effect of aging-related cognitive difficulties, these are language difficulties (for example, constrained word retrieval) that seem to be more directly involved in causing difficulties in sentence production in healthy aging (Kemper et al., 2001; Davidson et al., 2003). In AD, vocabulary and semantics are not only significantly disrupted, but are considered as a primary language symptom. Difficulties in verbal fluency and naming are prominent language characteristics of early, and even preclinical AD (Verma and Howard, 2012). Such difficulties are frequently linked to anomia, a key property of language disruption in AD. Anomia usually shows up as a general difficulty to access and recall words, resulting in a decline in both quantitative (number) and qualitative (type) presentation of lexical units (Banovic et al., 2018). Considering that changes in syntax do not appear until moderate dementia, with most errors relying on semantic deficits (Taler and Phillips, 2008), the lexical-semantic origin of such syntactic decline seems plausible. Word-finding difficulties in AD indeed lead to fragmentations and reduced coherence in language production. Similar parallels already exist at other linguistic levels, for example, in pragmatics, where disintegrated semantic knowledge predicts pragmatic disruptions, like difficulties in turn-taking or shifts in topic, or in the maintenance of conversations (cf. Van Boxtel and Lawyer, 2021). In their seminal study, Bates et al. (1995) suggested that syntactic deficits in AD are, at the abstract level, comparable to lexical deficits, in that they follow the pattern of inclusion of highly frequent or empty forms.

However, difficulties with syntactic processing and production in aging can also be due to the progressive disruption of cognitive functions properly. Healthy older adults show more errors in syntactic production due to difficulties in planning and production (Hardy et al., 2020). Crucially, tasks involving higher cognitive load (e.g., on working memory or episodic memory) unchain more acute syntactic difficulties and impairment in speakers with AD. The syntactic decline in dementia, thus, could be specific (or isolated), or otherwise result from a combination of language-cognition interplay (cf. Nasiri et al., 2022). The first option can be supported by evidence on pauses in AD discourse. Although pauses could reflect lexical retrieval difficulties, in aging they can also be the result of other types of decline, for example, global cognitive slowing down, or decline in discourse control and planning (Gayraud et al., 2011). Interestingly enough, speakers with AD present with increasing pausing in utterance-initial and clause-initial positions, suggesting difficulties in content planning and structural assembly of event representations (Lofgren and Hinzen, 2022). The second option is supported by evidence from fine-grained analyses of AD discourse. According to this, syntactic deviations in AD are not only due to deficits in formal syntactic competence but also to growing constraints for specificity in discourse referencing (e.g., in anaphoricity) (Chapin et al., 2022). In their recent fine-grained analysis, Chapin et al. (2022) related a set of syntactic changes in AD to the growing difficulty of speakers with dementia to relate events, create referential connections and, thus, establish and introduce new referents as measured by indefinite noun phrases.

Considering the above, in this paper we aim to address the etiological background of syntactic change in AD by applying the model of syntactic maturity, originally developed by Hunt (1965, 1970). In this model, the indexes of syntactic maturity do not measure the correction of the utterances, nor their internal organization (e.g., whether they are active or passive). Otherwise, they reflect how speakers cognitively support different syntactic structures by primarily considering overall embedded complexity. Consequently, the indexes of syntactic maturity directly reflect the global complexity of syntactic constituents, with no specific focus on their intrinsic internal properties. Importantly, this model allows weighting the proportion of complex over simple clauses with no effect from lexical indexes (like semantic adequacy or coherence), enabling a separation between lexical-semantic and syntactic levels.

To apply this model, our experimental design proposes the observation of possible changes in Hunt indexes in three groups of older adults: healthy speakers, speakers with AD, and speakers with MCI. MCI is commonly included in studies on cognitive and language changes in AD since in a number of cases [roughly, between 10 to 15% per annum (Shigemizu et al., 2020)] MCI can progress to dementia (Angelucci et al., 2010). Furthermore, MCI can allow the tracing of early markers of language performance in AD (Taler and Phillips, 2008). Importantly, the language performance of HC, MCI, and AD is suggested to represent a continuum of progressive, hierarchical decline in many language aspects (Liampas et al., 2022). Thus, we hypothesize that if syntactic complexity is affected in AD, speakers with MCI will also show a decline, albeit less pronounced.

Considering this, we applied the proposed model to our analysis of the Cookie-Theft description task (Goodglass et al., 2000) performed by healthy older speakers, speakers with MCI, and speakers with AD. The description of the Cookie-Theft picture minimizes the overload on memory (De Lira et al., 2014). Furthermore, our prediction was as follows: if speakers with AD present with syntactic decline on a task excluding significant overload on memory, then, such decline is syntactic in nature. This assumption considered findings from previous studies, which demonstrated more significant impairment in AD on more memory-demanding tasks (e.g., syntactic priming) than on less memory-demanding tasks (e.g., sentence completion), specifically following canonical ordering (Nasiri et al., 2022).

1.2. The model of syntactic maturity and its units of measurement

As stated above, the main aim of our study was to inquire into the background of syntactic changes in AD. Specifically, we wanted to test whether syntactic changes in dementia derive from the lexical-semantic deficit or, otherwise, are more autonomous in nature. In pursuit of this objective, we chose to apply the model of syntactic maturity, originally proposed by Hunt (1965, 1970) in their pioneering work in applied linguistics.

The notion of "syntactic maturity" is closely linked to that of syntactic complexity. Since the degree of syntactic complexity correlates with the speaker's capacity to express complex relations between ideas, mental states, and non-propositional actions (Beers and Nagy, 2009), its measurement is crucial for the evaluation of the speaker's cognitive state too. Hunt's model allows to assess how the full text or discourse produced by a speaker is organized in terms of the shortest grammatically allowable units (Adamson, 2019) and, at the same time, how complex these units are.

According to Hunt's model, syntactic maturity can be measured through primary indexes and secondary indexes. Primary indexes of syntactic maturity are measured as two types of units: *t-units* (also known as terminal units) and *clauses*. A t-unit is a main clause "plus all the subordinate clauses attached to or embedded in it" (Hunt, 1965, p. 141). Thus, for empirical analysis, any simple sentence, any sentence integrating a subordinate clause, and any proposition forming a sentence composed by coordination or juxtaposition, is considered as a t-unit (Delicia, 2011).

The second primary index of syntactic maturity is *clause*, which is defined as a subject (or a set of subjects) coordinated with a finite verb or a finite set of coordinated verbs, including impersonal verb forms (infinitive, gerund, or participle) when they do not form periphrases or semi-periphrases and act as a nucleus of a complex structure (Delicia, 2011). For empirical analysis, any clause embedded into a t-unit is considered a clause, allowing to measure how many clauses form each t-unit; this includes all simple, subordinate, and subordinating sentences. The ratio of clauses for t-units is taken as a measure of subordination (Beers and Nagy, 2009).

The interpretation of the indexes assumes that (a) the longer the t-units, (b) the higher the number of words per clause, and (c) the higher the proportion of clauses per t-unit (taken over 1), the higher the syntactic complexity (Delicia, 2011). To estimate the values of syntactic maturity, three indexes are calculated:

(a.) Index 1: mean length of t-units (the total number of words divided over the total number of t-units);
(b.) Index 2: mean length of clauses (the total number of words divided over the total number of clauses);
(c.) Index 3: the number of clauses divided over the number of t-units.

Table 1 shows examples of t-units and clauses from our sample. Specifically, it allows to see how clauses can be identified within t-units.

Hunt's model of syntactic maturity has been mainly applied to assessing normotypically developing child syntax. Yet, there have been some interesting contributions on syntactic change in language disorders from Hunt's model. Ketelaars et al. (2015) used Hunt's model to identify narrative deficits (mainly, narrative productivity) in children with pragmatic language impairment. Mozeiko et al. (2011) assessed t-units in speakers who suffered from traumatic brain injury (TBI) to find a significantly poorer performance in their grammar abilities. Pallickal and Hema (2019) also observed a significant reduction in t-units, but neither in the number of clauses nor in the number of words per clause in speakers with Wernicke's aphasia.

To the best of our knowledge, our study is the first one to apply Hunt's model of syntactic maturity in its original version for measuring syntactic competence in AD. Importantly, some studies already applied Hunt's model, although from a different perspective, to aging speakers. For example, Wainwright and Cannito (2015) analyzed t-units in older speakers to find them more prone to use referential ambiguities. Sajjadi et al. (2012) used the so-called "modified T-units" in order to analyze non-clausal utterances and message conveying in AD and semantic dementia, concluding their impairment in discourse construction. Against this background, in the present paper, we will apply the Hunt's model in its basic proposal to contribute to our understanding of the nature of syntactic changes in AD.

TABLE 1 Measures of analysis of syntactic maturity in AD.

Measure	Definition	Example*
t-unit <ut>	Any simple sentence; any sentence integrating a subordinate clause; any independent proposition forming a sentence composed by coordination or juxtaposition	<ut>Hay un niño que se ha subido a un taburete</ut> y <ut>está cogiendo galletas de una caja</ut>
Clause <cl>	Any simple sentence; any subordinate or and subordinating sentence within sentences ordered by subordination	<ut><cl>Hay un niño</cl> <cl>que se ha subido a un taburete</cl></ut> y <ut><cl>está cogiendo galletas de una caja</cl></ut>

*Original examples of this study have been obtained in Spanish. In this paper, we offer the original examples.

2. Methodology

2.1. Participants

A total of 60 older speakers participated in the study. Of these, 19 were diagnosed with MCI following the criteria of the International Working Group on Mild Cognitive Impairment (Winblad et al., 2004), and 20 were diagnosed by the National Health System with dementia of Alzheimer's type (AD) following the NIA-AA criteria (Jack et al., 2018). The remainder were 21 healthy older adults who formed the control group (HC). AD participants were recruited from the State Reference Center for the Care of People with Alzheimer's Disease and Other Dementias, Salamanca, Spain. HC and MCI participants were recruited from among attendees of the Psychological Attention Service for the Prevention of Cognitive Problems in the Elderly, City Psychosocial Support Unit, Council of Salamanca/University of Salamanca, Spain. The Service controlled for the classification of the cognitive state of the participants.

To participate in the study, HC had to meet the following inclusion criteria: be a native speaker of Spanish; be over 60 years old; have no history of drug or alcohol abuse; have no history of psychiatric illness; have no severe sensory deficits that would preclude the administration of cognitive tests; have a minimal level of schooling years to have acquired literacy; have no diagnosis of MCI or AD.

Speakers with MCI and AD had to meet the following inclusion criteria: be a native speaker of Spanish; be over 60 years old; have no history of drug or alcohol abuse; have no history of psychiatric illness; have no severe sensory deficits that would preclude the administration of cognitive tests; have a minimal level of schooling years to have acquired literacy. Furthermore, to be classified as MCI group, speakers had to be diagnosed according to the criteria from the International Working Group on Mild Cognitive Impairment (Winblad et al., 2004). To be classified as AD group, speakers had to be diagnosed by the National Health System with dementia of Alzheimer's type (AD) following the NIA-AA criteria (Jack et al., 2018).

All participants signed the informed consent form. The study was run in accordance with the Declaration of Helsinki and its subsequent amendments, as well as the European Union regulations for medical research. The study received the approval of the Ethics Committee of the State Reference Center for the Care of People with Alzheimer's Disease and Other Dementias, Salamanca, Spain.

The sample included a balanced number of participants per diagnostic group (variance = 0.695). The mean age of the sample was 77.65 years (SD = 8.79). The mean age of participants was higher in MCI and AD than in HC, and this difference was statistically significant [$F_{(2,57)} = 5.67$, $p = 0.006$, $\eta^2 = 0.166$], with the effect size indicating a large effect. *Post-hoc* analysis showed that the difference was only significant between HC and AD ($p = 0.005$).

Participants were predominantly women (n = 46; 76.7%), but there was no statistical significance in the distribution of

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participants according to sex across groups [$F_{(2,57)} = 0.75$, $p = 0.474$, $\eta^2 = 0.026$]. The mean duration of schooling (in years) was 9.40 years ($SD = 3.38$), ranging between 4 and 17 years. There was no significant difference for mean years of schooling across groups [$F_{(2,57)} = 1.375$, $p = 0.261$, $\eta^2 = 0.046$].

2.2. Instruments and neuropsychological assessment

All participants were assessed through the Dem-Detect toolkit (Peña-Casanova et al., 2009) for neuropsychological scoring. The cognitive assessment of each participant was conducted during three individual sessions of 1 h each.

Within a battery of neuropsychological tests, participants described the *Cookie-Theft picture* from the Boston Naming Test. All participants were given the same instruction to describe everything they can see in the picture. Speakers were recorded while performing the task with an iPad and a head-mounted condenser microphone, MiC plus from Apogee. Recordings were independently transcribed and annotated by two researchers following the established criteria.

2.3. Neuropsychological and language scoring

Neuropsychological and language tests were used for describing and controlling for the adequacy of the sample. Furthermore, these data will not be used beyond the characterization of its neuropsychological description.

Expectedly, groups varied on their scoring for MMSE test from Folstein et al. (1975) [$F_{(2,57)} = 25.120$, $p < 0.001$, $\eta^2 = 0.468$]. HC performed at an average higher than MCI (diff = 3.7, $p = 0.006$) and AD (diff = 7.93, $p < 0.001$), and MCI performed at an average higher than AD (diff = 4.23, $p = 0.002$).

Groups significantly varied on the semantic verbal fluency scale (SVF) as measured by Isaac's Set Test [$F_{(2,57)} = 13.593$, $p < 0.001$, $\eta^2 = 0.323$], in line with data provided by previous studies (Fisher et al., 2004; Amieva et al., 2005; Alegret et al., 2018; Liampas et al., 2022). HC showed the highest scores for SVF with the lowest SD ($M = 39.14$, $SD = 1.590$) and minimal scoring (35). MCI performed worse than HC ($M = 35.21$, $SD = 4.614$) and better than AD ($M = 29.05$, $SD = 9.682$), with minimal scoring achieving 24 and 14, respectively. Significant differences were observed between HC and AD ($p < 0.001$) and MCI and AD ($p = 0.009$), but not between HC and MCI ($p = 0.153$).

Groups also varied on the phonological verbal fluency scale (PVF) [$F_{(2,55)} = 21.016$, $p < 0.001$, $\eta^2 = 0.433$], a parameter for which significant between-group variation is not as systematic in evidence (cf. Teng et al., 2013). HC showed the highest scores for PVF ($M = 13.00$, $SD = 4.290$) and minimal scoring (6). MCI performed worse than HC ($M = 7.47$, $SD = 2.503$) and better than AD ($M = 5.67$, $SD = 4.044$), with minimal scoring achieving 4 and 1, respectively. Differences were significant between HC and MCI ($p < 0.001$) and HC and AD ($p < 0.001$), but not between MCI and AD ($p = 0.434$).

Table 2 summarizes the main neuropsychological and language data for the sample.

2.4. Transcription and annotation of syntactic data

All speech samples were transcribed as follows. Each recording was transliterated with no link to a specific diagnosis. Illegible sequences or words were transliterated like "XXX" for inclusion into the general word count. Non-language elements (e.g., noise, sustained sounds, etc.) and filled pauses (e.g., "mmmm") were not included. Repetitions (e.g., "su/su mama") and incomplete word forms (e.g., "cubiert-," for "cubiertos") were included. Fifteen of the 60 transcriptions (25%) were then double-checked for consistency, bordering the score of 1.

Each transcription was furthermore annotated. Identification and annotation of all categories were carried out according to a specifically designed label system for the measurement of syntactic maturity within the CORDEM corpus annotation system. Specifically, the following two labels were used: <ut></ut>, for T-Units, and <cl></cl> for clauses. To adjust the model of syntactic maturity to oral speech production, which can include non-verbal or syntagma-based utterances, as well as grammatically peripheric structures with discourse roles (e.g., discourse markers), we assumed that utterances where a verb could be possibly reconstructed [e.g., What do you see on this picture?—AD speaker: two kids = (There are/I see) two kids] would be considered as t-units.

For each transcription, the total number of produced words (n_1), the total number of unique produced words (n_2), and the global uttering time (s) were calculated. Data for each transcription was then merged into the global matrix of the sample to adjust to neuropsychological scores.

The following categories were collected and assessed within this model in our study:

- Total produced words (n);
- Total unique produced words (n);
- Global uttering time (excluding interviewer's utterances) (s);
- Number of t-units (<ut></ut>);
- Number of clauses (<cl></cl>);
- Mean length of t-units (Index 1);
- Mean length of clauses (Index 2);
- Mean of clauses/t-units (Index 3).

2.5. Statistical analysis

Statistical analysis was conducted using IBM SPSS Statistics for Windows (26.0). We used one-way ANOVA with Group (HC, MCI, and AD) as between-subject factor and ran it on the following dependent variables: age, sex, education level, Mini-Mental State Examination (MMSE) scoring, Semantic Verbal Fluency (SVF) scoring, Phonological Verbal Fluency (PVF) scoring, mean duration of speech production, overall produced words, overall full words, number of t-units, number of clauses,

TABLE 2 Sample: demographic data.

Group	Total		Mean age		Sex		Schooling (years)		MMSE		SVF		PVF	
	n	%	Mean	SD	M	W	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HC	21	35%	73.14^{+}	6.85	14.3%	85.7%	10.38	2.92	28.33^{*++}	1.82	39.14^{++}	1.59	13.00^{**++}	4.29
MCI	19	31.7%	78.42	10.27	26.3%	73.7%	8.84	3.65	24.63^{*+}	2.31	35.21*	4.61	7.47**	2.50
AD	20	33.3%	81.65^{+}	7.12	30%	70%	8.90	3.50	20.40$^{+/++}$	5.47	29.05^{*++}	9.68	5.67^{++}	4.04
Total	60	100%	77.65	8.79	14	46	9.40	3.38	24.52	4.83	34.53	7.44	8.91	4.84

$^{*}p < 0.05$.
$^{+}p < 0.05$.
$^{**}p < 0.001$.
$^{++}p < 0.001$.

TABLE 3 Time spent on the task and the total number of words produced by HC, MCI, and AD.

Group	Time spent (s)		Overall words		Total full words	
	Mean	SD	Mean	SD	Mean	SD
Control	48.14	16.03	108.95^{++}	38.40	104.04^{+}	36.72
MCI	39.63	21.19	82.52	46.33	81.89	46.03
AD	40.35	22.59	61.50^{++}	36.78	60.80^{+}	36.51
Total	42.85	20.10	84.76	44.54	82.61	43.10

$^{*}p < 0.05$.
$^{+}p < 0.05$.
$^{**}p < 0.001$.
$^{++}p < 0.001$.

Index 1, Index 2 and Index 3. *Post hoc* analyses were conducted using Bonferroni *post-hoc* test. Correlational analysis (Pearson's correlation) was used to measure the association between SVF and indexes of syntactic maturity.

3. Results

3.1. Time duration and overall word production

The mean duration of discourse production (measured in seconds) did not significantly differ across groups [$F_{(2,57)} = 1.131$, $p = 0.330$, $\eta^2 = 0.038$]. The mean duration for all groups was 42.85 s ($SD = 20.102$), with the following means for each group: HC = 48.142 ($SD = 16.038$), MCI = 39.631 ($SD = 21.192$), and AD = 40.35 ($SD = 22.597$).

The main effect of the group was significant in the number of overall words [$F_{(2,57)} = 7.047$, $p = 0.002$, $\eta^2 = 0.198$]. Yet, only HC and AD significantly differed in the number of overall words ($p = 0.001$), with HC producing 47.452 words more than AD. There were no significant differences in the number of overall words between HC and MCI ($p = 0.133$) and between MCI and AD ($p = 0.334$).

The main effect of the group was significant in the number of full words [$F_{(2,57)} = 6.041$, $p = 0.004$, $\eta^2 = 0.175$]. Again, only HC and AD significantly differed in the number of full words ($p = 0.003$), with HC producing 43.247 more full words than AD. There were no significant differences in the number of full words between HC and MCI ($p = 0.253$) and between MCI and AD ($p = 0.312$) (Table 3 and Figure 1).

3.2. T-units

Groups did not significantly vary in the number of t-units [$F_{(2,57)} = 0.912$, $p = 0.407$, $\eta^2 = 0.031$]. The means and SD for each group were: HC = 11.333 ($SD = 5.072$), MCI = 10.684 ($SD = 5.508$), and AD = 9.1 ($SD = 5.683$).

3.3. Clauses

Groups significantly varied in the number of clauses [$F_{(2,57)} = 3.630$, $p = 0.033$, $\eta^2 = 0.113$]. The means and SD for each group were: HC = 18.523 ($SD = 7.138$), MCI = 14.89 (SD = 7.59), and AD = 12.25 ($SD = 7.751$). Only HC and AD significantly differed in the number of produced clauses ($p = 0.029$). There were no significant differences in the number of clauses between HC and MCI ($p = 0.395$) and between MCI and AD ($p = 0.825$) (Figure 2).

3.4. Indexes of syntactic maturity

Significant differences were observed in all three indexes between groups.

Differences in Index 1 were statistically significant between groups [$F_{(2,57)} = 12.945$, $p < 0.001$, $\eta^2 = 0.312$]. The means and SD for each group were: HC = 10.37 ($SD = 3.24$), MCI = 7.53 ($SD = 2.06$), and AD = 6.72 ($SD = 1.55$). Index 1 was significantly different in HC compared to MCI ($p = 0.001$) and AD ($p < 0.001$). Differences in Index 1 were not significant between MCI and AD ($p = 0.912$).

Differences in Index 2 were statistically significant between groups [$F_{(2,57)} = 5.094$, $p = 0.009$, $\eta^2 = 0.152$]. The means and SD for each group were: HC = 5.95 ($SD = 0.62$), MCI = 5.38 ($SD = 1.43$), and AD = 4.78 ($SD = 1.32$). Index 2 was significantly different in HC compared to AD ($p = 0.007$). There were no significant differences in Index 2 between HC and MCI ($p = 0.390$) and MCI and AD ($p = 0.349$).

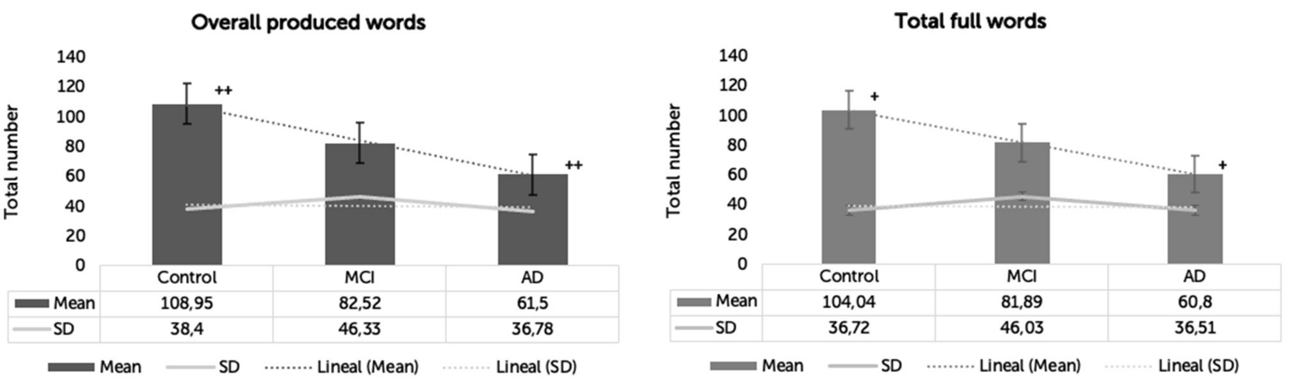

FIGURE 1
Overall words and total full words produced by clinical groups. *p < 0.05. +p < 0.05. **p < 0.001. ++p < 0.001.

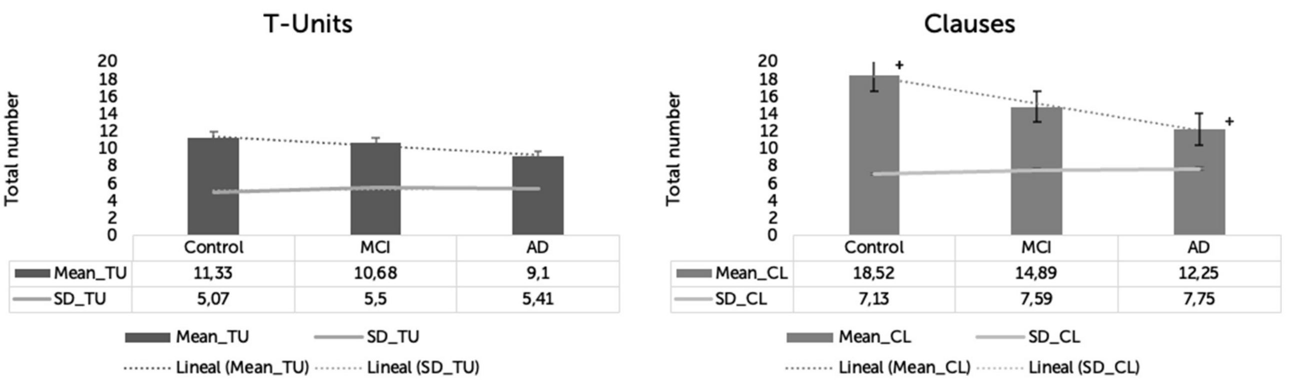

FIGURE 2
T-units and clauses produced by three groups in Cookie-Theft picture description task. *p < 0.05. +p < 0.05. **p < 0.001. ++p < 0.001.

Differences in Index 3 were statistically significant between groups [$F_{(2,57)} = 7.639$, $p = 0.001$, $\eta^2 = 0.211$]. The means and SD for each group were: HC = 1.72 (*SD* = 0.43), MCI = 1.39 (*SD* = 0.18), and AD = 1.32 (*SD* = 0.36). Index 3 was significantly different in HC compared to MCI ($p = 0.014$) and AD ($p = 0.002$). There were no significant differences in Index 3 between MCI and AD ($p = 1.000$) (Figure 3).

Overall, HC and AD significantly differed in all indexes of syntactic maturity, with all indexes being lower in AD. HC and MCI significantly differed in Index 1 and Index 3, and, crucially, MCI and AD did not differ in any of the indexes of syntactic maturity.

Our results suggest that, although HC, MCI, and AD do not differ in the number of t-units, speakers with dementia produce shorter t-units, shorter clauses, and t-units with fewer clauses than HC. Thus, all indexes of syntactic maturity are significantly different between healthy older adults and speakers with dementia. At the same time, our results do not show significant differences between HC and MCI, and MCI and AD in most measures. HC and MCI do not differ in the number of t-units and clauses, but they do differ in the mean length of t-units and their index of syntactic complexity as measured by the number of clauses per t-unit. Crucially, none of the indexes of syntactic maturity shows a significant difference between MCI and AD, suggesting that these two groups do not differ in their syntactic productions measured through Hunt's model.

Table 4 summarizes the results for all measures of syntactic maturity.

3.5. Syntactic indexes and lexical-semantic ability

To control for the possible correlation between lexical deficits and syntactic production in MCI and AD, we conducted correlation analyses between SVF scores and the three syntactic indexes of syntactic maturity.

We found positive correlations between SVF and Index 1 ($r = 0.327$, $p = 0.011$) and SVF and Index 2 ($r = 0.286$, $p = 0.026$), whereas the correlation between SVF and Index 3 was not significant ($r = 0.120$, $p = 0.360$).

4. Discussion

In the present study, we primarily aimed to address two questions. On the one hand, we pursued the to confirm whether

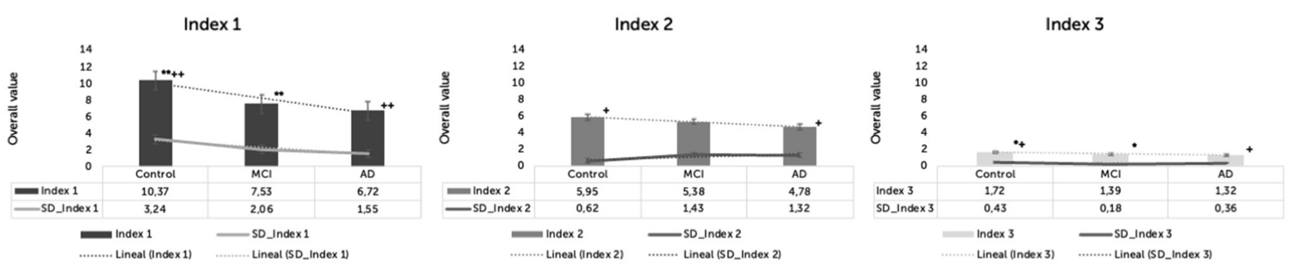

FIGURE 3
Indexes 1, 2, and 3 for three groups in the Cookie-Theft picture description task. $*p < 0.05$. $^{+}p < 0.05$. $**p < 0.001$. $^{++}p < 0.001$.

TABLE 4 Syntactic maturity measures in productions of speakers with HC, MCI, and AD.

Group	T-Units		Clauses		Index 1		Index 2		Index 3	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Control	11.33	5.07	18.52^{+}	7.13	10.37^{**++}	3.24	5.95^{+}	0.62	1.72^{*+}	0.43
MCI	10.68	5.50	14.89	7.59	7.53^{**}	2.06	5.38	1.43	1.39^{*}	0.18
AD	9.10	5.68	12.25^{+}	7.75	6.72^{++}	1.55	4.78^{+}	1.32	1.32^{+}	0.36
Total	10.38	5.41	15.28	7.81	8.26	2.86	5.38	1.25	1.48	0.38

$^{*}p < 0.05$.
$^{+}p < 0.05$.
$^{**}p < 0.001$.
$^{++}p < 0.001$.

syntactic ability significantly changes in AD, and whether such change can be also traced in MCI. On the other hand, we wanted to address the etiological background of such change in dementia, by focusing on its probable isolating (or autonomous) nature from other declines. To meet these objectives, we opted for the application of Hunt's model of syntactic maturity to the analysis of the descriptions of the Cookie-Theft picture. To the best of our knowledge, our study is the first to apply the original version of this model to speakers with MCI and AD. Based on the results, this study shows that changes in syntactic ability are already present at the MCI stage, though it is at the full AD stage that syntactic complexity is significantly different (that is, lower in all indexes) than in HC.

In line with many studies on syntax in AD (Croisile et al., 1996; De Lira et al., 2011; Bose et al., 2021; Liu et al., 2021), our research confirms that speakers with dementia present with changes in their syntactic ability. Importantly, such syntactic changes are not surface, that is, they do not affect the basic syntactic organization of speech in dementia, which is consistent with previous findings on the general preservation of syntax in pathological aging. Truly indeed, despite producing significantly fewer words than healthy older adults (almost half as much), speakers with AD organize them sequentially in a similar proportion of sentences. Importantly, the degree of in-group (speakers with AD) and between-group (HC vs. MCI vs. AD) homogeneity for this general ability is high.

According to our results, significant changes appear in qualitative aspects of syntax and, specifically, in complex syntax. The difference in the number of t-units is not statistically significant and this result is consistent with the previously reported *general preservation* of syntactic ability in dementia, and cognitive impairment stage, reported in the Introduction of this work.

Our results are, however, consistent with the view that it is syntactic complexity, as measured by embedding (clauses), which is significantly reduced in dementia. Despite producing a similar proportion of sentences, AD speakers produce shorter units (either sentences or clauses) and fewer subordinations than HC. Crucially, an important finding of this work is that MCI and AD do not differ on any index of syntactic complexity, suggesting that significant changes in syntactic maturity are already present at the MCI stage. Since HC and MCI significantly differ in the mean length of t-units and the proportion of clauses over t-units only, but not in the number of produced words, the number of t-units, the number of clauses, or the mean length of clauses, we suggest that the most important changes in syntax occur in the overall length of utterances and their index of complexity. A plausible explanation for syntactic changes in AD can be related to the decline in working memory, which is consistently reported in the literature (cf. Kirova et al., 2015), and the interaction of working memory decline and language problems themselves (Lee and Kim, 2019; Nasiri et al., 2022). The same argument could potentially explain the few changes observed between HC and MCI, relative to the decline in the length and the complexity of utterances. Yet, further studies would be needed to check the plausibility of this explanation for MCI at the language level, in line with studies suggesting general memory decline already in MCI (cf. Saunders and Summers, 2010).

Relevant to this latter observation is our result on the correlation between lexical-semantic performance and syntactic indexes of HC, MCI, and AD. Since the task we analyze in this paper minimizes the effect of cognitive load (being supported by images, speakers do not have to rely on episodic memory), we can assume that syntactic production is not constrained and, thus, can be manifested to the fullest. Furthermore, relative lexical freedom of the task (although conditioned by the picture, speakers can use synonyms or hypernyms) makes it more flexible considering possible lexical-semantic deficits. In fact, the model of syntactic complexity we use in this research allows us to disregard the possible effect of the lexical-semantic deficit on syntactic productions. Interestingly enough, correlation analysis of scores on SVF task and indexes of syntactic maturity showed that a better SVF predicts a higher length of either t-units or clauses in aging speakers, but not the index of complexity as measured by the proportion of embeddings. These results suggest that the syntactic complexity is not conditioned by the lexical-semantic deficit itself and, importantly, such observation is in line with other studies reporting cognitive, rather than linguistic predictors of syntactic performance in AD (cf. Nasiri et al., 2022).

Further, *ad-hoc* designed analyses are needed to confirm whether the syntactic change in AD is independent of specific cognitive dysfunctions. Both possibilities could potentially exist if we consider other language levels in AD. For example, several studies proved that lexical-semantic deficit in early dementia is not related to cognitive dysfunction. Auriacombe et al. (2006) observed that changes in category verbal fluency task are quantitatively, but not qualitatively significant in early AD. Put it differently: speakers with prodromal dementia produce fewer words, but they do not show deficits in repeating them. The authors interpreted this result as proof of primarily semantic, but not a directly involved cognitive deficit proper of dementia. Similar conclusions were formulated by Liampas et al. (2022), who related word-finding problems with predominant disruptions in semantic stores, and Andreetta and Marini (2015), who reported lexical impairment to be responsible for macrolinguistic difficulties and impairment in fluent aphasia.

These observations lead us to another important question: the relevance of the type of task (or stimuli) in collecting, analyzing, and interpreting data on syntax in dementia. As stated above, AD drives important disruptions in cognitive functions involved in language control, but also in the language function itself. Furthermore, different language tasks can unchain different degrees of the implication of cognitive functions and language components. In their seminal study based on the assessment of written texts, Kemper et al. (1993) concluded that AD speakers showed syntactic simplification but, at the same time, preserved syntactic grammaticality. By contrast, a longitudinal study from Eyigoz et al. (2020) showed that speakers with future onset of AD wrote texts based on telegraphic patterns, i.e., with reduced (or even absent) grammatical structures, lacking functional words (like determiners or auxiliaries), and frequent misspellings. The typology of the task is a probable root of such contradictory results.

Discussion about the type of stimuli, however, should not be simplistically considered from the differentiation of written and oral tasks. Oral tasks, which are more commonly applied to the assessment of language and cognitive performance of older speakers usually imply different cognitive overload. Thus, different degrees of spontaneity in oral tasks lead to different cognitive loads on speakers. It is assumed that, within such a gradation, the most spontaneous oral tasks are the most demanding, since, in addition to not allowing for planning or prior memorization, they also require a very high level of cognitive and memory control and activation (Guinn et al., 2014). Instead, picture-description tasks reduce cognitive demands by minimizing overload on memory, specifically on episodic memory (Chapin et al., 2022). As our own results show, the correct identification and selection of the task can be a determining factor in correctly accessing the complexity of syntactic phenomena in dementia.

Studying syntax in AD faces another important challenge: what should we consider a *baseline* for assessing grammatical decline in aging and dementia? In their other relevant study, Kemper et al. (2001) observed a considerable individual variation in the initial grammatical complexity of older adults. Further longitudinal studies (e.g., Ahmed et al., 2013) confirmed that the starting profile of AD, including its prodromal or probable stages, is heterogeneous in (baseline) language abilities. Furthermore, one of the challenges in measuring syntactic disruption is related to the definition of *what* is syntactic complexity, *how* we can correctly measure it, and what cognitive predictions can be made about it. Several indexes of syntactic complexity have been used in studies on AD considering their predictive cognitive load. For example, Pakhomov et al. (2011) developed a computerized linguistic analysis system (CLAS), which assessed AD-driven changes in syntactic complexity based on the indexes of utterance length (mean number of words), the mean number of clauses (number of S nodes in parse trees), the total Yngve depth index (number of branches below each node, from right to left), the total Frazier depth index (number of branches for each word in the path to the highest node), and the total syntactic dependency length (SDL; sum of all dependency distances in the serial position of the constituent words). Their results are promising, but we still lack data on the threshold levels of syntactic normotypicality in aging.

Another intriguing question we have tried to address in this work is to which extent possible syntactic deficit in AD can be affected or predicted by the lexical-semantic deficit. Results from some of the most relevant studies suggest that lexical and syntactic impairments (or changes) are potentially dissociated in AD. Fraser et al. (2016) observed that semantic and syntactic impairments are asymmetric, that is, are presented with very low correlation. In their referential study of Iris Murdoch's written language, Garrard et al. (2005) observed similar dissociation between lexical impairment and relative syntactic preservation, and, in both cases, authors related their findings to underlying neuropathological patterns primarily affecting the temporal lobe. In this study, we found that lexical-semantic ability (as measured by SVF) predicts performance in the length of utterances and embedded clauses, but not in the syntactic complexity.

Considering such dissociation, it is crucial to look for the reasons for syntactic simplification in AD. Many of the indexes that measure syntactic production are associated with working memory and processing ability. Yet, Pakhomov et al. (2011) also suggested that both working memory and semantic difficulties could jointly affect syntactic complexity. Since cognitive impairments in AD are related to both structural dysfunction and functional disconnections in brain networks (Montembeault et al., 2019), their pattern can be insightful for our understanding of syntax in dementia. Functional connectivity changes in the language network are specifically noticeable in the left posterior middle temporal gyrus (pMTG) of people with AD, and associations between such changes and lexical deficits (mainly naming and verbal fluency), which link pMTG with lexical-semantic retrieval, are reported (Mascali et al., 2018; Montembeault et al., 2019). So, one of the important contributions from AD to our understanding of syntax in the brain comes from the evidence of how AD-related neurodegenerative processes, and the corresponding syntactic deviations, align with the predicted neuroanatomical substrate for syntactic processing and production. Difficulties in syntactic comprehension can be linked to progressive volume loss in the left temporal lobe, comprising the Wernicke's area, which is responsible for the syntactic analysis of stimuli and, mainly, for the building up of the argument structure (Bickel et al., 2000). Yet, at the same time, the preservation of the general ability to produce syntax is coherent with the most recent findings about neuroanatomical support of syntactic abilities. Syntactic abilities in the human brain are *mainly* supported by the inferior frontal gyrus, particularly by Broca's area and, within this, by BA44, but complex syntax significantly relies on the interactive connection of BA44 with the superior temporal gyrus (STG) (Friederici et al., 2017). Furthermore, neuroanatomical and language interactions expectedly replicate each other.

As a final word, our results are in line with recent research from Chapin et al. (2022), who suggest the necessity to recur to fine-grained, rather than coarse analysis of syntax if we want to understand its true nature. The fine-grained analysis from Chapin et al. (2022) showed that specific syntactic elements (e.g., NP vs. VP) can show up with different changes, and be, furthermore, due to different etiologies. Our work confirms this position by underlying the need to specify *what* we measure in syntax, *how* we measure it, and what is *baseline* we have to consider for measuring it accordingly.

5. Conclusions

For a long time, syntax has been considerably disregarded from the study of language profiles in AD. The salience and the primacy of the lexical-semantic deficit in dementia have probably been one of the main reasons for such disregard. The preservation of general syntactic ability, reported by pioneering studies on syntax in AD, is another important factor. Truly indeed, speakers with AD can construct grammatically acceptable sentences, and, as this research shows, the number of sentences they build matches with the similar index in healthy aging and speakers with Mild Cognitive Impairment.

Yet, the application of the model of syntactic maturity allowed us to demonstrate that syntax is not fully preserved in AD and already changes at the MCI stage. Specifically, we observed that speakers with dementia produce significantly shorter sentences and clauses, and rely significantly less on subordination. Our results are in line with other recent studies (e.g., Chapin et al., 2022), which suggest the necessity of fine-grained analysis for disentangling the specificity of syntactic deficits in dementia. Considering that the task we analyze (Cookie-Theft picture description task) minimizes the effect of cognitive and lexical load, and that scoring in semantic tasks does not correlate with the index of syntactic complexity, we conclude that syntactic decline in AD parallels other language and cognitive declines.

Overall, several important questions must be addressed for a better understanding of syntax in pathological aging. First, we lack a necessary background for what normotypical syntax is and how we should measure it. This is crucial for answering the questions about the patterns of syntactic change in AD. Second, we need to specify better the type of stimuli for syntax elicitation. Different language tasks drive different loads on cognition and language, so, expectedly, syntactic outcomes can vary in due order. All in all, we believe that a better understanding of syntactic ability in AD can significantly improve our understanding of human syntactic ability, as well as its neurocognitive and theoretical relationship with other language levels.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Requests to access the data should be directed to OI at olga.ivanova@usal.es.

Ethics statement

The study received the approval of the Ethics Committee of the State Reference Centre for the Care of People with Alzheimer's Disease and Other Dementias (Salamanca, Spain), attached to the Spanish Ministry of Social Rights and 2030 Agenda. All participants signed the informed consent form. The study was conducted in accordance with the Declaration of Helsinki and its subsequent amendments and the European Union regulations concerning medical research.

Author contributions

OI and JM contributed to conception and design of the study. OI, IM-N, and EG-P organized the database. OI and JM performed the data analyses. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

OI and JM were declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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A reconceptualization of sentence production in post-stroke agrammatic aphasia: the Synergistic Processing Bottleneck model

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The language production deficit in post-stroke agrammatic aphasia (PSA-G) tends to result from lesions to the left inferior frontal gyrus (LIFG) and is characterized by a triad of symptoms: fragmented sentences, errors in functional morphology, and a dearth of verbs. Despite decades of research, the mechanisms underlying production patterns in PSA-G have been difficult to characterize. Two major impediments to progress may have been the view that it is a purely morphosyntactic disorder and the (sometimes overzealous) application of linguistic theory without interceding psycholinguistic evidence. In this paper, empirical evidence is examined to present an integrated portrait of language production in PSA-G and to evaluate the assumption of a syntax-specific syndrome. In light of extant evidence, it is proposed that agrammatic language production results from a combination of morphosyntactic, phonomotor, and processing capacity limitations that cause a cumulative processing bottleneck at the point of articulatory planning. This proposed Synergistic Processing Bottleneck model of PSA-G presents a testable framework for future research. The paper ends with recommendations for future research on PSA-G.

KEYWORDS
agrammatism, aphasia, syntax, morphology, phonology, processing load, verb

Introduction

Agrammatism, which refers to morphosyntactic impairment in post-stroke aphasia (PSA), has been a poster-child for the neurocognitive modularity of morphosyntactic processes. Agrammatic aphasia has also been a testing ground for linguistic theories and inferences about Broca's area function (e.g., Grodzinsky, 2000; Patel et al., 2008). Given that there are differences in the use of the diagnostic label of agrammatism, we clarify at the outset that this paper focuses on language *production* in *agrammatic post-stroke aphasia (PSA-G)*. While morphosyntactic impairments are also acquired from other etiologies such as neurodegeneration in primary progressive aphasias (PPA), this paper focuses on PSA-G because there is a significantly larger body of empirical and theoretical research on agrammatic post-stroke aphasia. Consequently, it allows for a more extensive synthesis of morphosyntactic production deficits following stroke. Further, by focusing on a single etiology, we avoid the (yet unconfirmed) assumption that the same neurocognitive mechanism underlies morphosyntactic impairment in both post-stroke and progressive aphasias. For instance, it is likely that domain-general bilateral neural circuitry is recruited to compensate for language deficits much earlier in the evolution of PPA (compared to PSA) given its insidious disease progression (Sonty et al., 2003; Canu et al., 2020). *Asyntactic comprehension*, which refers to the pattern of worse understanding of syntactically complex and semantically reversible sentences compared to syntactically simple sentences, is not uniquely and consistently associated with agrammatic production (Caramazza and Zurif, 1976; Miceli et al., 1983; Kolk and van Grunsven, 1985). It is found across a variety of aphasia subtypes, as well as in neurotypical speakers under high cognitive load (Caplan et al., 2007, 2013). Hence this paper views *morphosyntactic production deficits* as the core component of *PSA-G*.

Despite over four decades of research on PSA-G, there is not yet a comprehensive understanding of what kinds of deviations from normal sentence production *mechanism(s)* give rise to the symptom cluster of agrammatic language production. While there have been some mechanistic accounts of PSA-G, such as Pick's (1913) Economy of effort and Kolk's (1995) Time-based approach, most extant accounts of PSA-G are linguistic descriptions of a single symptom (e.g., Thompson, 2003). While these descriptive accounts have provided symptom details (e.g., grammatical functions of words are more impaired than their lexical functions, Boye and Bastiaanse, 2018), such accounts do not explain *why* a symptom occurs in PSA-G.

The goal of this paper is to describe a mechanistic model of language production in PSA-G as a way move forward from the current stalemate. The model, which is referred to as the *Synergistic Processing Bottleneck* model, views PSA-G's morphosyntactic deficit as part of a broader clinical profile and is developed from an integration of empirical findings on neurotypical and agrammatic sentence production. It provides a testable framework for future research. In the build-up to the model, this paper is organized as follows: First, issues of empirical rigor in PSA-G research are raised. Next, current empirical evidence on PSA-G symptoms is integrated and critically evaluated to constrain the symptoms that must be accommodated in any theory of PSA-G. Next, the complex clinical picture of PSA in which morphosyntactic deficits occur is presented as a rationale for broadening the theoretical view of PSA-G. Following this, extant theories of PSA-G are briefly discussed in their ability to account for the clinical profile of PSA-G. Finally, in the Discussion section, the Synergistic Processing Bottleneck model is presented as a synthesis of the syntactic and non-syntactic symptoms of PSA-G with current understanding of how sentence production unfolds in neurologically healthy speakers. The paper ends with recommendations for future agrammatism research.

Empirical rigor in PSA-G research

Issues of empirical rigor and reproducibility have been identified in PSA-G research by several authors (Caplan, 1995, 2001; Mauner, 1995; Caramazza et al., 2001; Martin, 2006; Faroqi-Shah, 2020). These issues have significantly weakened the inferences that could be made from the data and has partly contributed to the current standstill in agrammatism theories. The goal of this section is to highlight criteria for scientific rigor that are particularly relevant to the study of PSA-G.

Diagnosis of PSA-G

The first and most important criterion is the diagnosis of PSA-G. A scoping review found that two-thirds of studies do not report any language scores to document agrammatism; and nearly half of the studies do not operationally define the condition, using proxies such as non-fluent or Broca's aphasia (Faroqi-Shah, 2020). There is no explicit consensus on what constitutes "agrammatism" (Berndt and Caramazza, 1981; Miceli et al., 1989; Martin, 2006; Thompson and Bastiaanse, 2012; den Ouden et al., 2019). While early descriptions solely focused on language production symptoms (Pick, 1913; Kleist, 1916; Goodglass and Berko, 1960), the term has evolved (for some authors) to include a sentence comprehension deficit (Berndt and Caramazza, 1981; Grodzinsky, 1984; Avrutin, 2000). The notion of a comprehension deficit as a core symptom of agrammatic production deficit has surprisingly persisted despite numerous studies showing the dissociation between sentence production and comprehension deficits (Caramazza and Zurif, 1976; Berndt and Caramazza, 1981; Miceli et al., 1983; Kolk and van Grunsven, 1985; Martin et al., 1989). In fact, in their classic study, Caramazza and Zurif (1976) reported that both people with (Broca's aphasia) and without (conduction aphasia) agrammatic production showed the same pattern of sentence comprehension deficit.

Additionally, but to a lesser extent, there are different views on the association between agrammatic production and a slow rate of speech (non-fluency). For example, De Villiers (1974) analyzed the speech of non-fluent aphasic speakers with "varying degrees of grammatical impairment ranging from almost intact to severely impaired." (p. 38). Similarly, Saffran et al. (1989) described the narrative language of speakers who produced "sparse halting speech" (i.e., nonfluent) and divided these speakers into "agrammatic" and "non-fluent non-agrammatic" speakers (p. 446). However, this nuanced yet important distinction between non-fluency and agrammatism seems to have been lost to overzealous theoretical syntacticians in later years. In some studies of PSA-G, participants are recruited based on their non-fluent speech, but there is no further characterization of the nature of morphosyntactic production errors (as noted by Faroqi-Shah, 2020; for example see O'Grady and Lee, 2001). The importance of this relationship between non-fluency and agrammatism will be discussed in a later section.

In clinical settings, it is important to note that physicians may identify aphasia in a neurological examination, however they do not possess the specialized training or standardized assessments to diagnose and differentiate between motor speech and (subtypes of) linguistic deficits. Speech-language pathologists (SLP) are qualified and specially trained to delineate the nuances of communication impairments in aphasia such as speech versus language deficits. In the absence of speech-language pathologists in countries where such a profession does not exist, it is critical to operationalize the inclusionary and exclusionary criteria for PSA-G participants. This was elegantly achieved by Menn and Obler (1990) when comparing

PSA-G speakers across fourteen languages: "*Agrammatic by clinical standards* was defined as being moderately non-fluent, having slow and halting speech, with three or four words being the usual maximum uninterrupted string" (p. 14).

In light of the above ambiguities in operationally defining and diagnosing PSA-G, a critical step in assessing the internal and external validity of any study is whether the authors operationally defined agrammatism, described how participants were diagnosed as PSA-G, and characterized the morphosyntactic profile of participant symptoms. It is important to note whether authors define PSA-G as a purely production disorder, or also assume difficulties in complex sentence comprehension. In short, a study that provides relevant language and clinical characteristics of the participants has greater validity than one that just uses generic terms (e.g., non-fluent aphasia).

Experimental design and inferencing

A second criterion in determining empirical rigor of the findings is the inferential strength of the experimental design. Double dissociations are a key inferential tool in neuropsychological research (Caramazza, 1984; Crawford et al., 2003). This refers to the demonstration that two individuals (or clinical groups) show deficits that are the inverse of one another. For instance, a double dissociation between verb and noun deficits has been shown in agrammatic and anomic aphasia (Miceli et al., 1988; Zingeser and Berndt, 1990; Lee and Thompson, 2011a). However, a majority of PSA-G studies have no comparison group or use a neurotypical "control" group (Faroqi-Shah, 2020). When studies compare PSA-G with a neurotypical group, it shows a single dissociation in which one cannot delineate the unique characteristics of agrammatism from the general impact of aphasia. The inferential power of studies that do include an aphasic comparison (e.g., fluent aphasia or anomic aphasia) may be further weakened if they do not meet the first criterion of accurate diagnosis. An example of this paradox is the frequently cited case study of a double dissociation between regular and irregular past tense in non-fluent and fluent aphasia (Ullman et al., 1997). "Fluent aphasia" is an obscure diagnosis which includes PSA profiles as disparate as anomic aphasia (with mild word retrieval issues) and Wernicke's aphasia (with severe semantic, phonological and self-monitoring challenges). Another challenge in double dissociation studies is matching (or statistically addressing) overall aphasia severity across groups. When composite language scores on standardized tests are used, such as the Aphasia Quotient on the Western Aphasia Battery (Kertesz, 2006), persons with PSA-G tend to score more severely than the comparison group due to their severe production difficulties (see for example the PSA-G vs. non-PSA-G in Faroqi-Shah et al., 2020).

Mediating, moderating, and confounding factors

Another interpretive over-simplification in agrammatism research is the assumption that experimental task performance directly measures the underlying linguistic deficit(s) without other mediating or moderating factors. PSA respond well to speech-language therapy (Brady et al., 2016) and may have engaged in different intervention programs as well as self-guided (or care-giver guided) language practice before partaking in the research study. Thus, researchers rarely measure "pure agrammatism." For instance, *Script Training* is a popular and effective intervention for sentence production deficits (Cherney et al., 2008) which might result in the overuse of structural templates such as *I am x* (x = happy/hungry/eating) or *Noun is Verbing* (Mom is calling, Dog is eating, etc.). Even before intervention is initiated, for example in the acute phase of stroke, there are significant cognitive and fatigue issues that could mask agrammatism (Adamson et al., 2004; Engelter et al., 2006; Nys et al., 2007; Cumming et al., 2013). In fact, stroke results in a variety of cognitive deficits, which can be severe in PSA (Murray, 2012; Chapman and Hallowell, 2021; Faroqi-Shah et al., 2022b). Short-term memory and working memory have been particularly identified as influencing sentence production and comprehension in PSA and in neurotypical speakers (Caplan et al., 2013; Wright et al., 2014; Fyndanis et al., 2018; but see Ivanova and Ferreira, 2019). Cognitive deficits may limit the overall processing capacity for linguistic computations. Perceptual and motor impairments occur in nearly 74 and 85% of stroke survivors respectively and can be persistent (Mayo et al., 1999; Hazelton et al., 2022). There are also psychological effects of stroke such as depression, anxiety, and post-traumatic stress disorder, which are incident in nearly 70% of stroke survivors (Kauhanen et al., 2000; Assayag et al., 2022; Pompon et al., 2022; Skajaa et al., 2022). This is illustrated in Figure 1.

To summarize, PSA-G is one aspect of a multidimensional clinical profile, and numerous variables intervene between the actual morphosyntactic deficit and the empirical measure(s) obtained by researchers. These variables may affect experimental measures based on whether they are covariates, confounds, moderators, or mediators. A *covariate* affects the outcome variable but is not related to the independent variable (e.g., limb paresis for a keyboard response); a *confound* is associated with both the independent and dependent variables (e.g., short-term memory deficit), but does not drive the association between them; a *mediator* is a causal variable, such that the independent variable causes it, which in turn drives the dependent variable; and a *moderator* is not on the causal pathway but interacts with the independent variable in a way that drives the outcome (e.g., speech-language treatment) (Morrow et al., 2022). Currently, we lack a clear understanding of which (and how) different variables interact in PSA-G. This knowledge will not only improve how researchers statistically address and interpret outcome measures, but will also improve our understanding of individual variability in PSA-G. It is important to demonstrate how confounds from understanding task demands, memory demands, or lexical retrieval difficulties were addressed in data analysis and interpretation. For example, to address the fact that verb retrieval failures could confound the accuracy of producing verb inflections, Faroqi-Shah and Thompson (2004) analysis of the production of verb inflections only included verbs that were correctly named by each participant in a separate confrontation naming task. At minimum, a study should document screening of intuitive variables based on the experimental task, such as hearing loss and short-term memory for auditory comprehension and apraxia of speech (AoS) for verbal production (for example, see Szupica-Pyrzanowska et al., 2017).

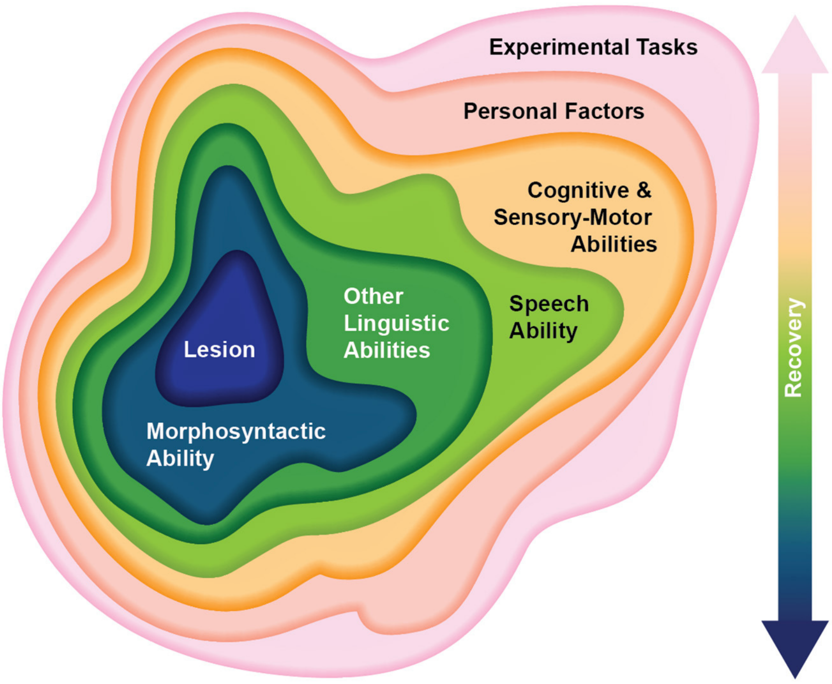

FIGURE 1
Epistemological framework of the complex clinical picture of post-stroke agrammatic aphasia. The key point is that numerous mediating, moderating, confounding and covarying factors intervene between the deficit (morphosyntactic ability) and the dependent variables measured in experimental tasks (outer layer). From the inner layer: Lesion refers to the anatomical integrity of gray and white matter, including structural and functional connectivity; Morphosyntactic ability is the key deficit of interest in agrammatic aphasia that researchers are trying to understand; Other linguistic abilities refer to concomitant language impairments in semantic, phonological, and orthographic domains; Speech ability represents concomitant non-linguistic impairments in motor control and execution (apraxia of speech and dysarthria) that can impact verbal production of language; Cognitive and Sensory-Motor abilities include any number of non-linguistic impairments resulting from stroke, such as short/long term memory, processing speed, processing capacity, attention, cognitive control, perception (including visual and auditory) and motor control (including limb paresis and praxis); Personal factors include a post-stroke mental disorders, fatigue, cultural and linguistic differences, education, task familiarity; Experimental tasks yield the dependent variables that researchers use to make inferences about morphosyntactic ability; and Recovery refers to the evolving severity of linguistic and non-linguistic abilities that is moderated by neurological recovery, speech-language therapy, and self-generated strategies. The sequence of the intervening layers is flexible.

Measurement reliability

The fourth criterion in demonstrating empirical rigor is the reliability of subjective measures of key dependent variables. When reporting accuracy of verbal productions, it is important to operationally define a correct response, describe how phonemic/semantic paraphasias were scored, and report how bias in scoring was addressed. For narrative language analyses, there are multiple sources of subjectivity, including transcription, utterance segmentation, and error coding. Ideally, studies should describe their reliability procedures including procedures for resolution of discrepancies, and should report inter-rater reliability (for sample studies that report reliability/consensus, see Rochon et al., 2000; Matchin and Hickok, 2020).

Summary of empirical rigor in PSA-G research

The four empirical issues listed in this section highlight the need to closely examine the methods adopted by PSA-G studies before drawing conclusions about what constitute the core symptoms of PSA-G and what mechanisms underlie the morphosyntactic impairment in PSA-G. In the following sections of this paper, to the extent possible, the above-mentioned criteria were applied to evaluate and select studies for discussion. That is, studies that provided a clear operational definition of agrammatic aphasia, detailed language and clinical characteristics of participants, reported double dissociations with appropriate statistical treatment, and addressed potential confounds in measurement of the dependent variable, were prioritized over studies that used vague terms (e.g., non-fluent aphasia) without language measures, and did not present a non-agrammatic PSA comparison (individual or group). Interpretations from meta-analyses were given more weight over individual studies as they wash out study-specific differences, and effects are computed over a larger number of participants. In the next section, empirical research is evaluated using these criteria in an attempt to identify the essential components of PSA-G.

Establishing the core morphosyntactic findings in PSA-G

"Boy... girl... cookie jar... mother... water... wash dishes." This utterance illustrates the triad of deficits that characterize PSA-G: fragmented utterances, errors on functional morphemes, and

missing verbs (Tissot et al., 1973; De Villiers, 1974; Goodglass, 1976; Saffran et al., 1989; Zingeser and Berndt, 1990; Goodglass et al., 1993; Bastiaanse and Thompson, 2012). These three symptoms are not mutually exclusive—a sentence may be fragmented because it is missing the verb and/or functional morphemes. Recent empirical support for this cluster of symptoms comes from a principal components analysis of 27 perceptual features of spoken language in an unselected group of English-speaking PSA (Casilio et al., 2019). The analysis found that four of the 27 features clustered together in aphasic speakers: stereotypies and automatisms, short and simplified utterances, omission of function words, and omission of bound morphemes. However, there is heterogeneity among PSA-G for the extent of these individual symptoms (Miceli et al., 1989; Rochon et al., 2000; Dickey and Thompson, 2009).

Following the seminal work of Caramazza and Zurif (1976), who reported difficulties in the comprehension of syntactically complex and semantically reversible sentences in Broca's and conduction aphasia (e.g., *The cow that the monkey is scaring is yellow*), some researchers included comprehension deficit as an additional symptom. This paper will refer to this comprehension pattern as *asyntactic* comprehension to avoid confusion with the triad of *agrammatic* production symptoms. This section will examine empirical findings for the above four symptoms to identify core symptoms that a theory of PSA-G should accommodate.

Sentence production

Three types of tasks have been utilized in PSA-G literature: (1) narrative samples elicited using story retell, picture descriptions, or personal experiences, (2) constrained elicitation of entire sentences or parts of sentences, and (3) arrangement of written word or phrase "anagrams" to construct a sentence. Comparisons across these tasks allow us to compare PSA-G's performance across different cognitive demands (and hence processing load), and delineate syntactic knowledge (anagram task) from performance deficits.

The following generalizations can be made by comparing findings across studies. First, about 30–50% of PSA-G's utterances are syntactically well-formed (Saffran et al., 1989; Rochon et al., 2000; Hsu and Thompson, 2018). Second, very severely impaired PSA-G individuals produce a predominance of 1-2 word fragments ("telegraphic speech") that does not show any semblance of word order. Such individuals also overuse stereotypical and automatic utterances (e.g., *Oh God, I don't know)* (Ishkhanyan et al., 2017). Third, the canonical word order of the speaker's language is preserved and is often over-used (Bates et al., 1987; Menn and Obler, 1990; Bastiaanse and Edwards, 2004). This has been interpreted as preservation of language-specific usage patterns (see also Bates et al., 1991; Gahl and Menn, 2016). Fourth, although their use of non-canonical sentence structures is limited, it is not clear that this pattern is unique to PSA-G because the same has been reported across aphasia categories and across elicitation tasks (Bates et al., 1991; Edwards, 1998; Faroqi-Shah and Thompson, 2003; Man et al., 2019). Fifth, word order errors or role reversals have been reported in both anagram and constrained picture descriptions. "A key unresolved question" about these errors is whether it reveals a failure of "function assignment" (Bock and Levelt, 1994). Function assignment refers to event conceptualization and ability to assign thematic functions to entities. Evidence points to relatively preserved function assignment based on the finding that the incidence of word order errors is low in anagram tasks (about 8.5% in: von Stockert and Bader, 1976; Saffran et al., 1980; Scholes, 1982). Further, when authors report error patterns in picture-sentence elicitation tasks, function assignment seems to be preserved. For example, Faroqi-Shah and Thompson (2003) compared passive sentence production between individuals with PSA-G and Wernicke's aphasia and varied the amount of lexical cues provided. Both groups showed similar accuracy of passive sentences across conditions. As is evident from the excerpts below, they also showed awareness of their role reversals. In short, there is no clear evidence suggesting a function assignment deficit in PSA-G.

> Broca's #7: *"The (the the) guy is helping the bicyclist... The other way around... The man is... The man is quaching the priest eh the bicycle."* (Target: The cyclist is helped by the hunter).
>
> Wernicke #4: *"Wife is going to cover the husband. That doesn't sound right. How do you do that?"* (Target: The wife is covered by the husband).

In addition to function assignment, PSA-G also show other preserved sentence production abilities. This includes responsiveness to structural priming, a phenomenon that is well-documented in neurotypical speakers (Bock and Loebell, 1990; Pickering and Ferreira, 2008). Cho-Reyes et al. (2016) used the classic structural priming paradigm where speakers repeat a prime sentence (e.g., passive or double-object dative) followed by describing a picture showing an action. Priming of sentence structure is indicated when speakers re-use the syntactic frame of the prime sentence in their picture description. PSA-G speakers not only showed structural priming effects, but also the magnitude of priming was comparable to neurotypical speakers (Cho-Reyes et al., 2016). However, there is considerable variability in the extent to which PSA respond to structural priming and produce complex sentences (den Ouden et al., 2019). Further, visual world paradigms (eye-tracking) show that PSA-G speakers plan their sentences incrementally, starting with the subject noun, just like neurotypical speakers (Lee and Thompson, 2011b; Lee et al., 2015). These studies show that the scope of sentence planning is similar to neurotypical speakers although the timecourse of planning is slower.

To summarize, PSA-G produce incomplete fragments and overuse canonical word order (Bates et al., 1987; Menn and Obler, 1990). There is no strong evidence to indicate that they have a deficit in activating complex syntactic structures from primed sentences, incremental planning, or function assignment (Lee and Thompson, 2011b; Lee et al., 2015; Cho-Reyes et al., 2016).

Functional morphology

Substitutions and omissions of free and bound functional morphemes are a hallmark feature of PSA-G across languages

(Bates et al., 1987; Menn and Obler, 1990; Casilio et al., 2019). When comparing PSA-G with other PSA, vulnerability of grammatical morphology seems to be particularly unique to PSA-G (Saffran et al., 1989; Menn and Obler, 1990; Bates et al., 1991; Goodglass et al., 1993; but see Haarmann and Kolk, 1992). Three aspects of functional morphology in PSA-G have been extensively studied. The first is the role of morphological complexity (e.g., Ullman et al., 1997; Lambon Ralph et al., 2005). Much of this work was framed within the dual route model of inflection, which proposed that regular and irregular inflections (e.g., past tense in English) utilize different neural mechanisms. The claim was a double dissociation such that regular inflections can be selectively impaired in PSA-G (e.g., Ullman et al., 1997). A meta-analysis of published data ($N = 75$) found no difference in the accuracy of regular vs. irregular verb inflections (Faroqi-Shah, 2007). In another study, PSA-G produced affixed verbs in 75% of their responses, showing no specific difficulty with affixation *per se* (Faroqi-Shah and Thompson, 2004). The meta-analysis and several other studies highlighted the confound between phonological and morphological complexity, not only because morphologically complex stimuli tend to be phonologically complex, but also because of the co-occurrence of both types of deficits in PSA-G (Obler et al., 1999; Kohn and Melvold, 2000; Bird et al., 2003; Braber et al., 2005; Faroqi-Shah et al., 2010; Szupica-Pyrzanowska et al., 2017).

The second topic of extensive research is the semantic and syntactic role subserved by the functional morphemes. Some morphemes refer to a component of the speaker's message, such as numerosity, event time, and pronominal reference, while other morphemes serve a syntactic well-formedness function, such as subject-verb agreement. The following picture of morphological production has emerged in PSA-G. Studies show that verb morphology is less accurately produced than noun morphology (e.g., plural and determiner) (Goodglass et al., 1993). Within verb morphology, tense marking is generally worse than agreement marking and non-finite verbs although there is some inter-individual variability (Wenzlaff and Clahsen, 2004; Faroqi-Shah and Thompson, 2007; Bastiaanse and Thompson, 2012; Fyndanis et al., 2012; Zhang and Hinzen, 2022; but see Burchert et al., 2005). A meta-analysis ($N = 143$) showed that there is no difference in accuracy among verb tenses, that is past vs. present vs. future tense (Faroqi-Shah and Friedman, 2015). Studies have found that tense comprehension is also impaired (Dickey et al., 2008) and this correlates with the magnitude of tense production deficit (Faroqi-Shah and Dickey, 2009).[1]

The third line of research has examined usage patterns. In terms of the relative frequency of occurrence of different morphemes, the proportions parallel what is found in neurotypical speakers of that language (De Villiers, 1974; Blackwell and Bates, 1995; Centeno et al., 1996; Centeno, 2007, 2012). That is, the best preserved morphemes are those that are most frequent in the language. This pattern mirrors the overuse of canonical word order described in the previous section (Menn and Obler, 1990; Bates et al., 1991). Beyond language use patterns that drive the overall occurrence of morphemes, Faroqi-Shah and Thompson (2004) found two patterns. First, there was a frequency effect in substitutions of verb inflections: more frequent inflectional variants of a verb (e.g., *cooking*) were produced for less frequent targets (e.g., *cooked*) (see also Centeno et al., 1996; Centeno, 2007). Second, individual participants with PSA-G overused a specific verb form. For example, CH overused *Verb+ing*, RH overused *Verb+ed* and LD overused the verb stem (Figure 2 in Faroqi-Shah and Thompson, 2004).

To conclude, verb morphology is particularly vulnerable in PSA-G (Goodglass et al., 1993). In languages that mark tense on the verb, the difficulty is found both in production and comprehension (Clahsen and Ali, 2009; Faroqi-Shah and Dickey, 2009). Language use patterns have a major influence on what is produced with an overuse of more frequent morphological forms and little effect of verb regularity or tense type (Faroqi-Shah, 2007; Faroqi-Shah and Friedman, 2015).

Verbs

A double dissociation between verb vs. noun retrieval in agrammatic vs. anomic aphasia was first reported in the late 1980s (Miceli et al., 1988; Zingeser and Berndt, 1990; Bates et al., 1991). Later studies found that verb deficits were not inherently tied to agrammatic (or Broca's) aphasia, and occurred in persons with fluent aphasia as well (Berndt et al., 1997b; Bastiaanse and Jonkers, 1998; Edwards, 1998; Matzig et al., 2009). A meta-analysis ($N = 175$) of picture naming data found that the pattern of worse verb naming was found across a majority of fluent and non-fluent persons with aphasia (Matzig et al., 2009). Irrespective of the presence of agrammatism, there is an association between reduced verb naming ability (measured with action picture naming) and the production of shorter sentences and impoverished sentence structure (Berndt et al., 1997a; Edwards, 1998; Speer and Wilshire, 2013). In summary, while verb retrieval deficits are not unique to PSA-G, there is nevertheless an association between verb retrieval and sentence elaboration deficits.

To elucidate the source of verb deficits in aphasia, investigators have examined dimensions along which verbs vary, such as transitivity, imageability, instrumentality, and noun homophony (Bastiaanse and Jonkers, 1998; Bird et al., 2000; Kim and Thompson, 2000, 2004; Arévalo et al., 2007; Stavrakaki et al., 2011). The logic is that these variables denote representational complexity of verbs, thus potentially influencing verb breakdown in aphasia. Two variables are particularly relevant to syntactic deficits: verb argument structure and verb weight. Syntactic complexity of a verb is often represented by verb argument structure (VAS), which refers to the number of arguments a verb requires and the number of different argument alternations the verb takes. Thompson's (2003) *Argument Structure Complexity Hypothesis* proposed that verbs with more complex VAS are more impaired in PSA-G. This pattern is supported in picture naming data, where PSA-G have been compared to comparison groups of Alzheimer's disease and anomic aphasia, showing a double dissociation (Kim and Thompson, 2004;

1 This study is frequently cited as evidence of a selective past tense impairment by Bastiaanse and colleagues (e.g., Bastiaanse and Thompson, 2012; Bastiaanse, 2013; Boye et al., 2023) although there was no significant difference across tenses (cf. Figure 2 in Faroqi-Shah and Dickey, 2009).

Cho-Reyes and Thompson, 2012). However, in picture naming, VAS is confounded by visual complexity of the pictures because verbs with more complex VAS (e.g., a ditransitive such as *giving*) are represented by a more complex visual scene compared to scenes that can be named by a verb with a simpler VAS (e.g., *barking*). Indeed, picture complexity is known to influence verb retrieval in neurotypical speakers (Szekely et al., 2005; Faroqi-Shah et al., 2021). The Argument Structure Complexity Hypothesis has not been borne out in narrative language, where VAS complexity effects have not been found (Webster et al., 2001; Malyutina and den Ouden, 2017). In fact, a large corpus study found that neurotypical and PSA speakers used a variety of verbs with simple and complex VAS. Persons with Broca's aphasia, however, used less complex and diverse VAS elaborations compared to other speaker groups (Malyutina and den Ouden, 2017) and produced fewer adjuncts (Zhang and Hinzen, 2022). If Broca's aphasia is taken as a proxy for PSA-G, then it appears that although verbs are used in sentences, their VAS may not be fully elaborated. Consistent with this, in constrained sentence production tasks where participants are required to retrieve the verb and its arguments to produce a complete sentence, sentences with complex VAS verbs are less well-formed and less complex compared to sentences with simpler VAS verbs (e.g., Dragoy and Bastiaanse, 2010; Malyutina and Zelenkova, 2020). However, it is unclear if this finding is specific to PSA-G because studies either report single dissociations (e.g., Dragoy and Bastiaanse, 2010), insufficiently characterize the morphosyntactic production deficit of PSA-G ("nonfluent" participants in Malyutina and Zelenkova, 2020), or find no differences across aphasia subtypes (Jonkers and Bastiaanse, 1996; Caley et al., 2017; Malyutina and Zelenkova, 2020). While some studies have noted that syntactic complexity has an additive effect with VAS complexity (e.g., Bastiaanse and van Zonneveld, 1998, 2005), other studies have not found this effect (Kok et al., 2007). In an eye-tracking study in which real-time access to verb argument structure information was examined, PSA-G showed spared access to overtly expressed VAS, but showed delays in retrieving VAS information when the argument was not explicitly provided (Mack et al., 2013).

Another dimension of verb complexity is its semantic specificity, referred to as verb weight. At one extreme are light verbs, a specific subset of very frequent, semantically underspecified verbs whose meaning can vary widely according to context (e.g., go, do, make, give). Light verbs are often grammaticalized cross-linguistically (i.e., behave like grammatical morphemes) and take a diverse variety of complements, making them syntactically complex. Heavy verbs, which are semantically more specific, were contrasted with light verbs by Gordon and Dell (2003) in the *Division of Labor* hypothesis between semantics and syntax. It was proposed that aphasic persons with weaker syntactic abilities would be worse at producing light verbs and vice versa. These predictions were borne out in double dissociations (Kim and Thompson, 2004; Barde et al., 2006). This division of labor between semantic and syntactic complexity of verbs was further supported in a large corpus of 164 persons with aphasia, which found a trade-off (negative correlation) between verb naming in confrontation (most of which are heavy verbs) and (1) light verb use and (2) syntactic productivity (Thorne and Faroqi-Shah, 2016) (replicating Berndt et al., 1997a; Webster et al., 2001).

To summarize the empirical findings on verb deficit in PSA-G, they show a paucity of verbs in narrative language, due to which a verb deficit is recognized as one of the three core symptoms of the agrammatic production (e.g., Tissot et al., 1973). Across PSA subtypes (not just PSA-G), there is a negative association between verb retrieval abilities at the single word level and sentence well-formedness and complexity (Berndt et al., 1997a; Thorne and Faroqi-Shah, 2016). In picture naming tasks where a single word label is elicited, both PSA-G and non-agrammatic PSA show verb retrieval difficulties (e.g., Matzig et al., 2009). In picture naming, there is some evidence of double dissociations between PSA-G and other groups regarding verb argument structure complexity (Cho-Reyes and Thompson, 2012). When verbs are used in sentences and narratives, there is insufficient evidence to suggest that VAS complexity drives verb selection in PSA-G (Jonkers and Bastiaanse, 1996; Malyutina and den Ouden, 2017). However, extrapolating from Broca's aphasia, it is likely that VAS *elaboration* is limited in PSA-G (Malyutina and den Ouden, 2017). Finally, PSA with syntactic deficits produce fewer light verbs (Thorne and Faroqi-Shah, 2016). It should be pointed out that there are some empirical confounds in investigations of argument structure complexity in PSA-G: the action pictures used as stimuli may differ across VAS types by imageability, visual complexity, or picture name agreement. Additionally, sentences with complex VAS are frequently longer than sentences with simpler VAS. Thus other co-occurring deficits such as lexical retrieval or scope of incremental planning might limit the production of sentences with complex VAS verbs.

Sentence comprehension

Asyntactic comprehension in PSA-G generated immense interest between the 1980s and 2000s (Grodzinsky, 1984, 1988; Zurif et al., 1993; Caplan et al., 2007). Across a variety of comprehension tasks, the following conclusions can be made from studies that were more empirically robust (e.g., Berndt, 1991; Caplan et al., 2007, 2013; Pregla et al., 2022). Asyntactic comprehension is found across neurotypical speakers and across PSA subtypes (Caplan et al., 2007, 2013; see also Wilson and Saygin, 2004; Pregla et al., 2022). In neurotypical speakers and mild aphasia, the pattern of asyntactic comprehension is trigged by the difficulty of the experimental task (Murray et al., 1997; Caplan et al., 2013). Based on these findings, asyntactic comprehension has been attributed to processing/resource limitations rather than a syntactic deficit in agrammatism (Caplan, 2012; Caplan et al., 2013).

Several studies have examined the ability of PSA-G to judge the grammaticality of sentences across a variety of sentence types (Linebarger et al., 1983; Baum, 1989; Wulfeck et al., 1991; Grodzinsky and Finkel, 1996; Devescovi et al., 1997; Kim and Thompson, 2000; Dickey and Thompson, 2009; Faroqi-Shah and Dickey, 2009; Faroqi-Shah et al., 2020). The pattern that emerges from these studies is that grammaticality judgement of most sentence structures is preserved in PSA-G (e.g., wh-questions, verb argument structure violations), the only consistent exception being tense violations (e.g., Dickey et al., 2008), and a few other long-distance dependencies (Baum, 1989).

Summary of core morphosyntactic characteristics of PSA-G

To conclude this section, the most empirically robust findings in PSA-G are impairments in: producing well-formed sentences, elaborating verbs with their arguments in sentence contexts, and producing and comprehending verb tense morphology. Impairments in closely associated processes, such as knowledge of verb argument structure, verb affixation, and function assignment are not implicated in PSA-G. Finally, asyntactic comprehension is not uniquely associated with PSA-G (e.g., Wilson and Saygin, 2004) and is more likely a generic response to higher processing demands (Caplan, 2012).

Re-envisioning PSA-G in a broader cluster of symptoms

A morphosyntactic profile of PSA-G has emerged from the synthesis of evidence in the previous section. However, this is an incomplete portrayal of PSA-G because agrammatic production is one symptom within the broader clinical profile of post-stroke aphasia resulting from left inferior frontal gyrus (LIFG) lesions. Some of these "non-syntactic" aspects are closely associated with PSA-G, such as a slow speaking rate and symptom variability (e.g., Kok et al., 2007; Gordon and Clough, 2020; Gleichgerrcht et al., 2021), while others are characteristic of aphasia in general, such as phonological and cognitive deficits, and use of compensatory strategies to accommodate linguistic deficits (e.g., Braber et al., 2005; Chapman and Hallowell, 2021). Yet others are the consequence of stroke, such as slowed processing speed, perceptuo-motor impairments, and depression (Assayag et al., 2022; Hazelton et al., 2022; Yoo et al., 2022). Figure 1 illustrates the complexity and dynamics of factors at play in PSA-G. The inner layers reflect linguistic attributes most closely associated with PSA-G and the outer layers represent symptoms found across aphasias and stroke survivors. It is very likely that these multiple strata interact in complex ways that are yet to be understood. Therefore it is important to view PSA-G as an amalgamation of cognitive and linguistic symptoms resulting from LIFG lesions. Progress toward a comprehensive theory of PSA-G can be made by accommodating this interaction between the morphosyntactic profile and other non-syntactic behaviors, to the extent that the latter are relatively consistent in PSA-G.

In this section, I will highlight several findings that are inherent in the clinical picture of PSA-G and are overlooked in current theories of agrammatism. Some of these findings question the assumption that PSA-G is a purely morphosyntactic disorder and argue for an expanded view of PSA-G that incorporates other linguistic deficits. Other findings provide insights into cognitive mechanisms that could be implicated as the underlying source of agrammatic aphasia. Evidence for broadening of the linguistic profile of PSA-G will be drawn from the high co-occurrence of slow speech rate along with motoric and phonological deficits. Indications of likely mechanisms that lead to agrammatic language output will be taken from the multiple and synchronized functions subserved by LIFG, and inter- and intra-individual variability documented in PSA-G.

Broca's aphasia, apraxia of speech, and phonological errors

Broca's aphasia is used as a proxy for PSA-G by numerous researchers (e.g., Patel et al., 2008; Boye and Bastiaanse, 2018). To better understand PSA-G, let us sift through the symptoms that constitute Broca's aphasia. Standardized assessments of aphasia characterize Broca's aphasia with the following multidimensional profile: subjective identification of fragmented utterances produced at a slow rate, impaired ability to repeat, and relatively preserved auditory comprehension (Goodglass et al., 2001; Swinburn et al., 2004; Kertesz, 2006). In the Western Aphasia Battery-Revised (WAB-R, Kertesz, 2006), which is the most commonly used standardized test (Kertesz, 2020), Broca's aphasia is identified with scores for fluency, comprehension, repetition, and naming in the range of <5, 4–10, <7.9 and <9 respectively (on a scale of 0–10). Of particular relevance is the lower repetition score, which could occur due to phonological deficits and/or short-term memory limitations. Indeed, phonological errors are widely reported in Broca's aphasia (Trost and Canter, 1974; Monoi et al., 1983; Niemi et al., 1985) and this is relevant in the context of PSA-G for at least three reasons. First, morphologically complex words, which are often challenging for PSA-G, are confounded by phonological complexity. Thus, substitution and omissions of bound morphemes (e.g., *kick* or *kicking* for *kicks*) could be an artifact of phonological challenges, as demonstrated in several studies of PSA-G (Obler et al., 1999; Braber et al., 2005; Lambon Ralph et al., 2005; Faroqi-Shah et al., 2010). In fact, several lesion studies have demonstrated the proximity of lesions associated with syntactic deficits and phonomotor deficits (Borovsky et al., 2007; Faroqi-Shah et al., 2014; Na et al., 2022). This is illustrated in Figure 2.

Secondly, errors in repeating multisyllabic words and phoneme distortions are also a hallmark of motor planning difficulty in apraxia of speech, a symptom that co-occurs with and has lesion overlap with Broca's aphasia (Hillis et al., 2004; Richardson et al., 2012; Trupe et al., 2013; Basilakos et al., 2015; Ballard et al., 2016). In fact, AoS is fairly common, occurring in 30% of PSA (Ziegler et al., 2022). Third, den Ouden et al. (2019) reported that PSA-G had more severe apraxia of speech and slower speech rate compared to non-agrammatic PSA. To summarize, PSA-G is one symptom of this broader clinical picture of Broca's aphasia. Importantly, while there is evidence indicating that agrammatic language co-occurs, and is even confounded by, motoric and phonological difficulties, there is *no evidence* to date indicating that the morphosyntactic deficits of PSA-G occur in isolation without any other linguistic deficits. In the absence of such evidence, it is prudent to question the wisdom of conceptualizing PSA-G as an insular deficit.

Non-fluency

As with the proxy use of Broca's aphasia discussed in the previous section, researchers and clinicians use *non-fluent aphasia* as a proxy term and often use speech rate to diagnose agrammatism (Gordon and Clough, 2020). The distinction between non-fluency and agrammatic production is important because: (1) a slow rate of speech (non-fluency) could arise from a variety of underlying

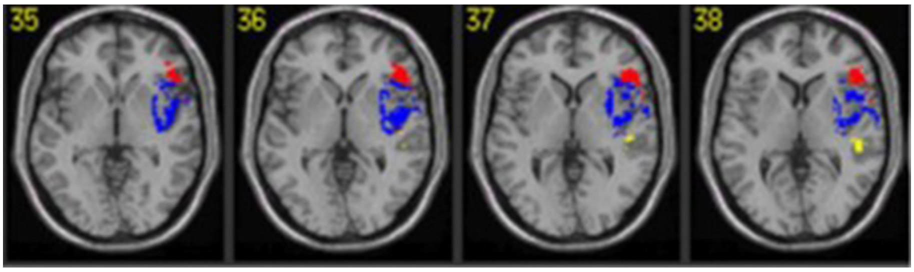

FIGURE 2
The proximity of lesions for sentence production (red) and phonological (blue) deficits from a voxel wise lesion symptom mapping study of aphasia (Faroqi-Shah et al., 2014). Reprinted with permission from Taylor & Francis Group.

reasons such as apraxia of speech, difficulty selecting between competing responses (dynamic aphasia), and/or excessive self-monitoring; (2) some fluent aphasias may be on a continuum with Broca's aphasia, and (3) fluency ratings can be unreliable (Gordon, 1998). In the multidimensional classification of aphasia, four subtypes are considered non-fluent (global, Broca's, transcortical motor, and transcortical mixed). Two critical questions are posed here. The first is whether there is a clearly delineated perceptual dichotomy between fluent and non-fluent aphasia given that accurate diagnosis of PSA-G is critical for empirical rigor. The second question is whether we can establish any relationship between PSA-G and slow rate. Evidence for this is evaluated next.

Fluent – non-fluent dichotomy

Despite the ubiquitous use of terms like fluent and non-fluent, there is little published data on their actual rates of speech. In the past few years, two studies analyzed the relationship between rate of speech and other language measures although neither study provides numerical values (Nozari and Faroqi-Shah, 2017; Gordon and Clough, 2020). The data from the 112 unselected PSA in Nozari and Faroqi-Shah (2017) was used to plot the distribution of rate of speech, measured as words per second, in Figure 3. It is noteworthy that the distribution is not bimodal, questioning the dichotomous distinction between fluent and non-fluent. Furthermore, Gordon (2020) reported that most disagreements of aphasia subtyping occurred between Broca's aphasia and two fluent aphasia types: anomic and conduction aphasia (illustrated in Figure 3 in Gordon, 2020). There is considerable overlap in the WAB-R profile scores of Broca's aphasia presented earlier (fluency, comprehension, repetition, and naming: <5, 4–10, <7.9 and <9 respectively) with those for conduction aphasia (>4, 7–10, <6.9 and <10 respectively; Kertesz, 2006). Furthermore, behaviorally, both Broca's and conduction aphasic individuals produce phonological paraphasias with self-corrections and have "functional" comprehension. These two subtypes can thus be viewed on a continuum as they evolve over time with recovery (Pedersen et al., 2004; Flowers et al., 2016). In fact, the overlap and continuity between Broca's and conduction aphasia may explain the similar performance of these two groups in the classic finding of asyntactic comprehension by Caramazza and Zurif (1976). These evidences not only underscore the over-simplification of the non-fluent-fluent dichotomy utilized in agrammatism research (Bates et al., 1991), but also caution against assumptions that a purely syntactic deficit exists in aphasia.

Relationship between non-fluency and morphosyntactic deficits

A critical question is whether slow speech rate and morphosyntactic deficits are a happenstance co-occurrence or whether there could be a mechanistic relationship between these two symptoms. Here we examine data from studies that examined the relationship between morphosyntactic abilities and some aspect of speaking rate (Nozari and Faroqi-Shah, 2017; Faroqi-Shah et al., 2022a; Salis and DeDe, 2022). In light of the previous critique of the fluent-non-fluent dichotomy, it is noteworthy that all three studies examined morphosyntactic abilities in aphasia as a continuous variable instead of using a categorical diagnosis of PSA-G. Nozari and Faroqi-Shah (2017) examined this question using a path analysis of narrative language samples of 112 persons with PSA (from MacWhinney et al., 2011). Non-fluency (measured as words per second and the WAB-R fluency rating, Kertesz, 2006) was most strongly predicted by morphosyntactic ability (path coefficient = 0.45) and to a smaller extent by lexical abilities, comprehension, and working memory (path coefficients = 0.11 to.13). The results of a new path analysis for morphosyntactic ability as the dependent measure are shown in Figure 4 (using data from Nozari and Faroqi-Shah, 2017). Morphosyntactic ability is represented by the Developmental Sentence Score (DSS, Lee and Canter, 1971). DSS provides a composite measure of an individual's morphosyntactic ability by locating eight types of morphosyntactic elements in the narrative sample and assigning weights to these based on age of acquisition norms (see also Thorne and Faroqi-Shah, 2016). The predictive contribution of speech rate (words/second) was the largest, more so than verb morphology (% past tense), comprehension (WAB-R), and verb retrieval (% verbs) (path coefficients are in Figure 4).

In another investigation of the relationship between speech fluency and morphosyntactic abilities, we measured the occurrence of disfluencies, such as filled pauses (uh, um, you know, etc.) and silences (Faroqi-Shah et al., 2022a). Disfluencies are interpreted as stalling for time for linguistic planning (Clark and Fox Tree, 2002; Howell, 2007; Salis and DeDe, 2022). Faroqi-Shah et al. (2022a) used relative scores of two continuous language measures, morphosyntactic productivity (DSS, Lee and Canter, 1971), and lexical diversity (Malvern and Richards, 1997), to calculate a

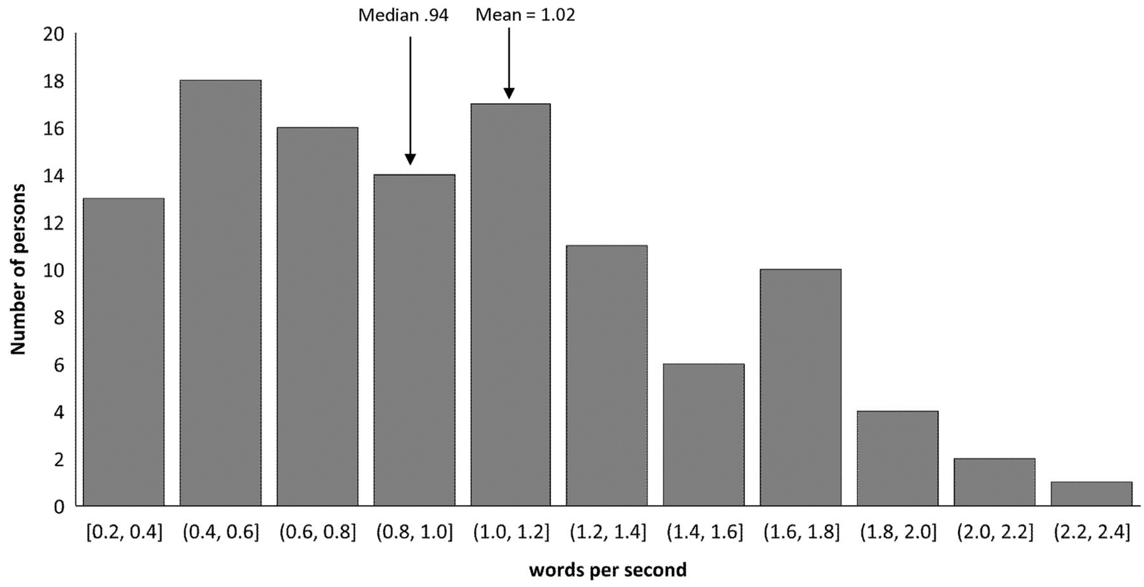

FIGURE 3
Distribution of rate of speech (words per second) in sample of 112 persons with aphasia (calculated from Nozari and Faroqi-Shah, 2017). The numbers on the x-axis refer to the range of speech rates that are represented in each frequency column.

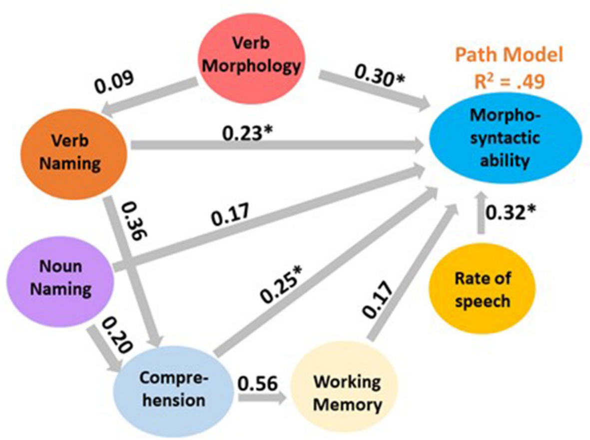

FIGURE 4
Results of a path analysis (with data from Nozari and Faroqi-Shah, 2017) showing the predictors for morphosyntactic productivity, as measured by the Developmental Syntax Score (Lee and Canter, 1971). For simplicity only the latent variables are shown. Numbers above the arrows represent the path coefficients, *significant predictors.

difference score (the Standardized Syntax Semantics Difference Score, SSSD). The SSSD was used to categorize participants into those with predominantly morphosyntactic (PSA-G) or lexico-semantic (PSA-LS) deficits. Individuals with predominantly morphosyntactic deficits produced more disfluencies overall (40% disfluencies vs. 29%). Figure 5 shows the proportion of filled pauses as a function of DSS for each group. The stronger association between disfluencies and DSS for the morphosyntactic deficit group indicates that this group is more likely to stall for time when speaking (Figure 5). This suggests an association between non-fluency and morphosyntactic deficit. Pause length is another metric of language fluency. Salis and DeDe (2022) found that longer pauses occurred within longer sentences in the narratives of mildly aphasic and neurotypical speakers. Thus syntactic planning has a time cost and individuals with proficient syntactic competence utilize pauses for syntactic planning. Summarizing across the three studies, the emerging picture is a strong association between morphosyntactic planning and speaking time, as shown in a path analysis (Figure 4), the higher occurrence of disfluencies in people with predominantly morphosyntactic deficits (Faroqi-Shah et al., 2022a) and those who successfully produce longer utterances (Salis and DeDe, 2022). While the latter two findings might appear contradictory, the common theme is that syntactic planning is associated with a high time cost. The implication of timing for a future theory of PSA-G is further analyzed in the Discussion section.

Inter- and intra-person variability

Individual variability in morphosyntactic performance is well documented, both within participants due to task demands (Hofstede and Kolk, 1994; Caplan et al., 2007; Kok et al., 2007; Pregla et al., 2022) and across individuals with agrammatic aphasia (Berndt, 1987; Miceli et al., 1989; Rochon et al., 2000; Caramazza et al., 2001; Faroqi-Shah and Thompson, 2004; Drai, 2006). Inter-person variability is unsurprising in light of the complex clinical profile of PSA discussed earlier (Figure 1). It also begs the question of whether PSA-G is a binary clinical condition, or whether agrammatic production lies on a continuum. Arguments in favor of a continuum view are that symptoms such as simplified sentence structure, morphological errors, and impaired comprehension of complex sentences are also found in other aphasia subtypes (Heeschen and Kolk, 1988; Bates et al., 1991;

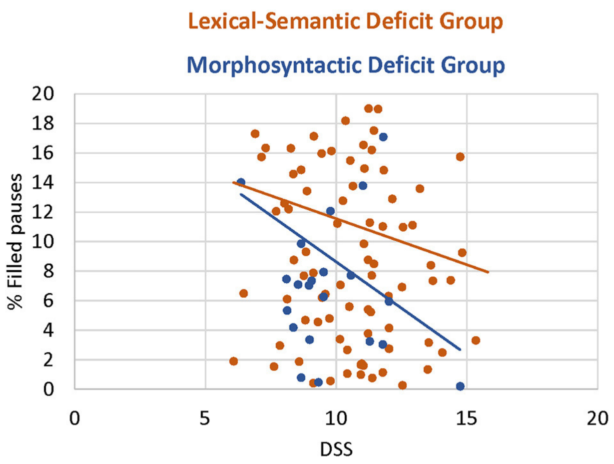

FIGURE 5
The relationship between filled pauses and deficit group in a narrative language analysis of disfluencies (from Faroqi-Shah et al., 2022a).

Edwards, 1998; Edwards and Bastiaanse, 1998; Caplan et al., 2007). Several authors have used continuous measures such as the percent of grammatical utterances, mean length of utterance, and DSS to measure morphosyntactic ability (Thompson et al., 2012; Thorne and Faroqi-Shah, 2016). This is not to say that a binary classification of PSA-G is problematic or futile: it is possible that persons who are clinically judged as "agrammatic" are at the extreme end of this continuum. And investigations contrasting groups at the extreme ends will be valuable in delineating the core characteristics of morphosyntactic impairment in aphasia.

Intra-person variability that occurs due to task demands or stimulus properties underscores a fundamental property of morphosyntactic computations: momentary variations in processing load impact the success of the computation. As an illustration of processing load effects on morphosyntactic computation, PSA-G produced more verb inflection errors when required to sequence words into a sentence and inflect the verb compared to just inflecting the verb (Kok et al., 2007; see also Slevc and Martin, 2016). Similarly, passive sentences were more accurately produced and comprehended with passive-bias verbs than with verbs that more commonly occur in active sentences (Gahl, 2002; Menn et al., 2003), and were more accurately produced when passive-morphology was cued (Faroqi-Shah and Thompson, 2003). In light of the inter-and intra-person variability in PSA-G, the logical approach forward is to accommodate the variability into future theoretical accounts of morphosyntactic deficits.

Lesion of the left inferior frontal region

Across studies, agrammatic language production in PSA is unambiguously and consistently associated with large lesions of the left inferior frontal gyrus (LIFG) and underlying white matter connections (Faroqi-Shah et al., 2014; den Ouden et al., 2019; Matchin and Hickok, 2020; Gleichgerrcht et al., 2021). Other lesions, such as those in the left posterior temporal or parietal cortex, have been less consistently implicated for morphosyntactic production deficits (e.g., den Ouden et al., 2019; Gleichgerrcht et al., 2021). The association between LIFG lesions and PSA-G is unsurprising given extensive evidence of the critical role of LIFG for morphosyntactic operations in neurotypical speakers (Embick et al., 2000; Shapiro and Caramazza, 2003; Sahin et al., 2006; Shapiro et al., 2006; Zaccarella et al., 2017). A key point, however, is that the LIFG is not a purely syntactic region, but is involved in several other linguistic operations at various time points during language encoding. This was demonstrated by Sahin et al. (2009) using intracranial recordings as people read or inflected words. LIFG activity occurred sequentially for lexical (∼200 milliseconds), morphological (∼320 milliseconds), and phonological (∼450 milliseconds) processing. Simply put, the LIFG is the end-stage hub for the highly coordinated encoding of lexical, morphosyntactic, and phonological representations for different elements in the sentence (Sahin et al., 2009; see also Zhu et al., 2022). Therefore LIFG lesions could not only affect morphosyntactic computations, but also other linguistic functions that could be critical for sentence production and directly contribute to the manifestation of PSA-G. Correspondingly, LIFG lesions have been implicated for deficits in phonological encoding (Borovsky et al., 2007; Indefrey, 2011; Faroqi-Shah et al., 2014; Flinker et al., 2015; Na et al., 2022), motor planning (Basilakos et al., 2018; Papitto et al., 2020), and word selection (Robinson et al., 1998; Swick et al., 2008; Schnur et al., 2009; Novick et al., 2010; Python et al., 2018).

In fact, the LIFG is an anatomically and functionally heterogeneous region (Amunts et al., 1999; Tettamanti and Weniger, 2006; Clos et al., 2013; Fedorenko and Blank, 2020; Asano et al., 2022) that has been implicated not only for the linguistic encoding mentioned earlier, but also for high level cognitive functions such as selection, sequencing, and inhibition (Fadiga et al., 2009; Schnur et al., 2009; Kunert et al., 2015; Maffei et al., 2020; Kemmerer, 2022). Several authors have argued that the LIFG is a domain- general (or supramodal) high level processing region (Tettamanti and Weniger, 2006; Clos et al., 2013; Fedorenko and Blank, 2020). It is also part of the multiple demand network that helps modulate brain activity when there are high processing load demands (Duncan, 2010). Given LIFG's role in multiple linguistic and cognitive functions, it is important to consider the cumulative impact of the LIFG lesion in PSA-G. For instance, it is likely that individuals with PSA-G have reduced overall processing capacity resulting from their LIFG lesions (Tettamanti and Weniger, 2006; Fedorenko and Blank, 2020). Thus they are unable to handle the high and time-constrained processing demands of sentence production as effectively as other PSA who do not have LIFG lesions. A future theory that accommodates the cumulative impact of LIFG damage on the processing demands of sentence production will better reflect the functional reality of this region and will be a step closer to a mechanistic explanation of PSA-G.

Summary of PSA-G as a broader symptom cluster

To summarize, this section presented evidence of the co-occurrence of non-syntactic deficits in individuals with PSA-G, particularly impairments in phonological encoding, motor planning, and speech fluency. Moreover, LIFG lesions, which are the primary etiology of PSA-G, have also been implicated for these non-syntactic impairments. Based on this evidence, it is prudent to view PSA-G not as an isolated syntactic deficit but as a symptom complex that includes phonomotor difficulties. This blending of morphosyntactic and phonomotor deficits is not an entirely novel idea, and has been proposed earlier [Pick, 1913; Kean, 1977 (cited in Akhutina, 2016); Kolk and Heeschen, 1992]. In light of the evidence presented in this section, there is currently no strong rationale to pursue theoretical accounts of an isolated syntactic deficit in aphasia. To move toward a theoretical account for the broader PSA-G symptom complex, this section drew attention to the widely reported phenomenon of symptom variability in PSA-G. Inter-individual variability may stem from the different extents of syntactic and phonomotor deficits across individuals. Intra-individual (task-based) variability may reflect the (in)ability of the LIFG-lesioned language network to handle the momentary processing and integration demands of the sentence being formulated. The next section evaluates current theories of PSA-G in the context of the broader PSA-G symptom cluster presented here and the core symptoms of PSA-G identified in the preceding section.

Extant theories of PSA-G

Given the non-specificity of asyntactic comprehension across aphasia subtypes (Caramazza and Zurif, 1976; Wilson and Saygin, 2004; Caplan et al., 2007), this section will focus on accounts of agrammatic production. Numerous theories of agrammatism have been proposed in the past four decades. Most extant models view PSA-G as a purely morphosyntactic disorder. Most models also focus on one aspect of the agrammatic symptom cluster such as asyntactic comprehension (Zurif, 1998; Salis and Edwards, 2008), verb complexity (Thompson, 2003; Barde et al., 2006), or verb tense morphology (Friedmann and Grodzinsky, 1997; Faroqi-Shah and Thompson, 2007; Fyndanis et al., 2012). A sample of these theories is given in Table 1.

Although a detailed discussion of these theories is beyond the scope of the present paper, a few key observations are highlighted. Extant theories fall into two broad genres: linguistic and mechanistic. Studies of PSA-G have been dominated by the application of linguistic theories to specific symptoms (e.g., Grodzinsky, 1984; Friedmann and Grodzinsky, 1997; Boye and Bastiaanse, 2018). These investigations align a linguistic theory with a specific symptom dissociation in PSA-G. In a recent example of this approach, Boye and Bastiaanse (2018) and Boye et al. (2023) used the contrast between grammatical and lexical functions of different words to show that the former word class is deficient in PSA-G (per the ProGram theory, Harder and Boye, 2011). However, PSA-G's dissociation in these two word classes has been documented for decades and formalized in prior theories such as the closed-class theory of agrammatism (Bradley et al., 1980; Biassou et al., 1997). Another example of a linguistic account, which prompted a large body of cross-linguistic investigations of PSA-G, focused on hierarchies of functional categories in the syntactic tree structure (Friedmann and Grodzinsky, 1997). Such linguistically-oriented studies have yielded detailed symptom descriptions of PSA-G (e.g., Wenzlaff and Clahsen, 2004; Burchert et al., 2005; Duman et al., 2007). Besides their focus on single symptoms, linguistically descriptive accounts have done little to advance current understanding of the underlying neurocognitive source of PSA-G. That is, these accounts do not explain *why* the symptom occurs in PSA-G. Further, most of these accounts lack linking data from neurotypical speakers that attests to the psychological reality of the identified linguistic computation.

Mechanistic theories, in contrast, attempt to explain the observed symptoms using one or more cognitive process(es) or strategies. In general, these theories implicate a unitary cognitive mechanism (or deficit) to explain a cluster of PSA-G symptoms. Some examples of these accounts include Pick's (1913) Economy of Effort, Bates and MacWhinney's (1987) Competition Model, Kolk's (1995) Time-based approach, Ullman's (2001) Declarative Procedural Hypothesis, and Gordon and Dell's (2003) Division of Labor. Unlike linguistic theories, few mechanistic theories adopt a purely syntactic view of agrammatism, thus more easily accommodating the multi-faced clinical picture of PSA-G. The general limitations of this genre of theories include insufficient delineation of how (or why) PSA-G differ from non-agrammatic PSA, and the limited efforts to empirically validate their predictions. Of course, the linguistic-mechanistic distinction of theories is not entirely binary, and some theories incorporate elements of both. For example, the Trace-Deletion Hypothesis for asyntactic comprehension suggests that persons with PSA-G have lost movement-traces and compensate for the absence of linguistic computation by applying heuristic strategies (Grodzinsky, 1984).

Summary of PSA-G theories and considerations for a future theory

The numerous theories of PSA-G that have been proposed (Table 1) broadly fall under a descriptive or a mechanistic label. While the former genre of theories tend to focus on a single symptom, the predictions of the latter genre have not been sufficiently tested. As yet, no theory of agrammatism explains the complete picture of PSA-G findings that has emerged over the past few decades. Of particular relevance for a comprehensive theory are the following observations. First, the theory must accommodate the core morphosyntactic symptoms that are uniquely associated with PSA-G: fragmented sentences, difficulty with functional morphology, especially tense marking, and elaboration of verb argument structure. Second, the theory must accommodate PSA-G's preserved abilities for some syntactic computations such as structural priming, incremental planning, and sensitivity to some syntactic violations. Third, the co-occurrence of non-syntactic deficits such as phonomotor deficits and non-fluency, needs to be accommodated. Conversely, there needs to be strong rationale for proposing an exclusive syntactic deficit. Fourth, symptom variability needs to be accommodated. While inter-individual variability can be easily explained by differences in lesion extent or co-morbidities, within-individual variability from task demands is tricky to explain. Further, a well-founded theory should not only account for the core symptoms of PSA-G but also delineate the mechanism underlying the paradox of other PSA (e.g., Wernicke's and conduction aphasia) who are able to formulate sentences with

TABLE 1 An illustrative selection of theories of agrammatism in post-stroke aphasia, presented in chronological order.

Year	Theory	Symptom(s)	Reference(s)
1913	Economy of effort	Omissions of closed class and bound morphemes	Pick, 1913
1976	Use of heuristics	Asyntactic comprehension	Caramazza and Zurif, 1976; Frazier and Friederici, 1991
1977	Phonological simplification	Omission of bound morphemes	Kean, 1977
1978	Closed class theory and its modifications	Omissions of closed class and bound morphemes	Bradley et al., 1980; Friederici, 1982; Bates et al., 1991
1984	Trace deletion hypothesis	Asyntactic comprehension	Grodzinsky, 1984, 1986
1985	Adaptation theory	Fragmented speech	Kolk, 1995
1987	Competition model	Language specific patterns are better preserved	Bates and MacWhinney, 1987
1991	Usage-based account(s)	Language specific patterns are better preserved	Bates et al., 1991; Gahl and Menn, 2016
1995	Time-based approach (slow activation, fast decay)	Fragmented speech	Friederici, 1995; Kolk, 1995; Swinney and Zurif, 1995
1997	Tree pruning	Differential impairment of functional categories (e.g., tense vs. agreement)	Friedmann and Grodzinsky, 1997
1997	Dual route model	Regular past is more impaired than irregular past	Ullman et al., 1997
2003	Argument structure complexity hypothesis	Verbs with complex verb argument structure are impaired	Thompson, 2003
2003	Shared syntax resource hypothesis	Asyntactic Comprehension	Patel, 2003
2003	Division of labor	Light vs. heavy verbs	Gordon and Dell, 2003
2004	Tense under-specification	Errors in verb tense	Wenzlaff and Clahsen, 2004
2004	Tense and agreement under-specification	Differential impairment of functional categories	Burchert et al., 2005
2005	Derived order problem hypothesis	Non-canonical sentence structures are more impaired	Bastiaanse and van Zonneveld, 2005
2007	Diacritical encoding and retrieval	Errors in verb tense	Faroqi-Shah and Thompson, 2007
2007	Resource reduction hypothesis	Asyntactic comprehension	Caplan et al., 2007; Caplan, 2012
2008	Set partition	wh-question comprehension	Salis and Edwards, 2008
2008	Slow processing of syntax	Asyntactic comprehension	Zurif et al., 1993
2011	Past discourse linking hypothesis	Past tense is worse than other tenses	Bastiaanse and Thompson, 2012
2012	Interpretable features impairment hypothesis	Differential impairment of functional categories	Nanousi et al., 2006; Varlakosta et al., 2006; Fyndanis et al., 2012
2015	Intervener hypothesis	Asyntactic comprehension	Sheppard et al., 2015
2016	Grammatical encoding co-occurrence	Differential impairment of functional categories	Duffield, 2016
2018	Usage-based account(s)	Grammatical words worse than lexical words	Boye and Bastiaanse, 2018
2022	Processability theory	Syntactic simplification hierarchy	Dyson et al., 2022
2022	Rational behavior	Omissions of closed class and bound morphemes	Fedorenko et al., 2022

relatively better sentence structure at a fluent speaking rate. Indeed, there is a critical gap in the current mechanistic understanding of how lexical, grammatical, motoric, and cognitive processes work together to enable fluent sentence production in neurotypical adults and how this breaks down in PSA-G. In summary, there are numerous compelling reasons to re-envision PSA-G within a theoretical framework that accommodates and integrates several findings that are unaddressed by current theories. Other authors have also recently revisited the theoretical framework of PSA-G (Dyson et al., 2022; Fedorenko et al., 2022).

Discussion

The goal of this paper is to develop a theoretical account of neurocognitive mechanism(s) underlying PSA-G that integrates the range of empirical findings and extends our understanding of the condition. The previous sections identified several reasons that have impeded advances in the understanding of PSA-G. A major factor that has stymied progress is the rigor and reproducibility of the empirical evidence, which is weakened by inconsistencies in patient characterization and failure to meet the minimum inferential assumptions of neuropsychological research (Caramazza, 1984; Bezeau and Graves, 2001; Martin, 2006; Gaeta and Brydges, 2020). The second issue is the narrow focus on morphosyntax, when in fact, morphosyntactic deficits do not occur in a vacuum. These are but one of a cluster of co-occurring symptoms in PSA-G, particularly phonomotor deficits and non-fluency (Kean, 1977; Goodglass and Kaplan, 1983; Blumstein, 2000). Further justification for broadening the view of PSA-G beyond a purely syntactic deficit comes from the multifunctional nature of the LIFG, whose lesions are the most consistent etiology of PSA-G. Third, a majority of current PSA-G theories are descriptive, in which linguistic theory is mapped onto any one PSA-G symptom, often lacking an actual explanation of why the symptom occurs. While there are some mechanistic accounts of PSA-G (e.g., Kolk, 1995), there isn't yet a sufficient body of empirical evidence to validate these accounts.

Gaps in the current understanding of neurocognitive mechanisms underlying PSA-G can be bridged by drawing from psycholinguistic findings of how neurotypical speakers formulate sentences. Mechanisms of neurotypical sentence production can be used as a framework within which to compare aphasic performance. This approach was taken by Thompson and colleagues in a series of studies comparing real-time encoding of sentences across agrammatic and neurotypical speakers using eye-tracking methods (Lee and Thompson, 2011b; Mack et al., 2013; Lee et al., 2015; Cho-Reyes et al., 2016). These studies are a valuable first step in uncovering specific aspects of sentence planning, such as incremental encoding of verb arguments. In the ideal world, we would have comparisons of real time performance across speakers who are neurotypical, PSA without agrammatism, and PSA-G. Comparisons across the first two groups would delineate the general impact of aphasia (including word retrieval difficulties), while comparisons across the latter two groups would pinpoint why some aphasic speakers formulate fairly well-formed sentences while PSA-G do not. In the next section, pertinent findings of constituent assembly in neurotypical speakers are presented so that these findings can be integrated into a theory of PSA-G. This is an alternate approach to the linguistic theory approach that is so prevalent in PSA-G research. Neurotypical findings of constituent assembly will be used as a backdrop to present the Synergistic Processing Bottleneck model. The rationale and key assumptions of this model are presented, followed by unanswered questions that await further research.

Integrating psycholinguistic findings to inform a theory of agrammatism

A common approach in testing theories of PSA-G is to compare their accuracy in simple constrained tasks (e.g., sentence completion) with neurotypical speakers whose performance is close to ceiling. In addition to the inferential weakness of this single dissociation approach, the near perfect accuracy of neurotypical speakers misses a key linking element: how do neurotypical speakers operate during sentence production, and how do those neurotypical phenomena inform mechanisms underlying PSA-G. As a way to move forward, this section will overview four key findings pertaining to sentence planning in neurotypical speakers that could inform a theory of PSA-G. The findings were selected to align with the PSA-G symptoms discussed earlier.

Following a classic language production model (Bock and Levelt, 1994), we use the term *constituent assembly* to refer to syntactic computations that combine two linguistic units, resulting in words (e.g., [stem]+[affix]), phrases, or hierarchical syntactic structures. Some of these computations fulfill an element of the speaker's message (e.g., tense) while others fulfill language-specific well-formedness constraints (e.g., subject-verb agreement for gender or number).

Constituent assembly proceeds incrementally

Several studies have shown that speakers do not plan an entire sentence before they speak. Rather they plan utterances incrementally such that earlier occurring lexical nodes (or "syntactic treelets") are planned and proceed on to articulatory planning before the next lexical node is planned (Griffin and Bock, 2000; Ferreira and Swets, 2002; Timmermans et al., 2012). This means that, when producing a subject-verb-object type of sentence (e.g., *The boy ate a sandwich*), the verb phrase is being syntactically planned simultaneously as the subject noun phrase is in some stage of phonological-articulatory planning. This has implications for PSA-G's reduced processing capacity, as was demonstrated by Lee and Thompson (2011b). They examined eye-fixations on adjuncts (e.g., picture of *restaurant* in the target sentence, *The boy ate a sandwich at the restaurant*). While neurotypical adults' eye-fixations on the adjunct occurred as they were speaking earlier parts of the sentence, PSA-G's fixations occurred before sentence onset. PSA-G's looks on the adjuncts prior to initiating the sentence show their difficulty in simultaneously planning and speaking, which is required for incremental sentence planning. It is also possible that PSA-G's difficulties with incremental planning are reflected in their slow speech rate and high proportion of disfluencies relative to other PSA (Nozari and Faroqi-Shah, 2017; Faroqi-Shah et al., 2022b).

Constituent assembly hinges on verb retrieval

Constituent assembly proceeds only after obligatory lexical elements are accessed. Evidence comes from the dependence of speech onset times on when the verb (Antón-Méndez, 2020) and its internal arguments (Momma et al., 2016, 2018) become available. For example, Antón-Méndez (2020) manipulated when each picture of a person-action-thing scenario was presented (e.g., pictures of baby, eating, and egg for the target sentence *The baby is eating an egg*). Sentence initiation times aligned with the presentation of the action picture although speakers had the opportunity to plan the subject phrase incrementally before retrieving the action. Next, a verb (or other lexical node) first needs to be retrieved before its grammatical morphemes can be planned. Evidence for this comes from longer speaking times for phonologically matched grammatical (e.g., *is* in *The bird is flying*) vs. lexical verbs (e.g., *is* in *The bird is black*) (Lange et al., 2017). In both instances, the lexeme *is* occurs as the third word in the sentence, but takes longer to articulate as a grammatical element because its planning hinges on the main verb *flying*. These psycholinguistic realities explain why verb retrieval difficulties are associated with impoverished sentences in PSA

(Berndt et al., 1997a; Thorne and Faroqi-Shah, 2016). The crucial role of verb retrieval in PSA is also evident in the path analysis in Figure 4 where verb retrieval, but not noun retrieval predicted sentence production.

Constituent assembly is computationally demanding

There is evidence for the large computational demands and scope of planning of constituent assembly (Allum and Wheeldon, 2007). This is indicated by several findings. First, speakers take longer or make more errors in utterance planning when there is a high processing load or under processing capacity limitations (Ferreira and Swets, 2002; Sikora et al., 2016; Slevc and Martin, 2016; Fyndanis et al., 2018). The fact that neurotypical and PSA speakers take advantage of lexical and syntactic accessibility in structural priming paradigms further points to the computationally intense nature of constituent planning (Faroqi-Shah and Thompson, 2003; Lee et al., 2015; Cho-Reyes et al., 2016). Next, neurotypical speakers as well as those with aphasia show a trade-off between syntactic complexity and lexical-semantic richness in sentence production (Thorne and Faroqi-Shah, 2016; Rezaii et al., 2022). For example, in utterances with low frequency words, neurotypical speakers use high frequency syntactic frames (and vice versa), showing that the computational demands of sentence planning necessitate a balance between syntactic and lexical load (Rezaii et al., 2022). PSA with syntactic deficits produce more semantically specific words while those with lexical-semantic deficits produce semantically lighter words (Thorne and Faroqi-Shah, 2016). Similarly, speakers with a variety of diagnoses show a trade-off between syntactic complexity (or sentence length) and phonological and motor complexity (Silverman and Ratner, 1997; Obler et al., 1999; Marshall and van der Lely, 2006; Walsh and Smith, 2011). These trade-offs indicate that constituent assembly is computationally demanding and is compromised when other linguistic processes require computational resources. For PSA-G in particular, the frequent co-occurrence of phonological/phonetic difficulties (Blumstein, 2000) and apraxia of speech (Trupe et al., 2013) in Broca's aphasia likely diminishes computational resources that are available for constituent assembly.

The LIFG is a core neural hub for constituent assembly

There is a rigorous body of neuroimaging research examining the spatial and temporal correlates of constituent assembly, including the production of words, phrases, and inflectional morphemes (Indefrey et al., 2001; Shapiro et al., 2006; Sahin et al., 2009; Roos and Piai, 2020; Hauptman et al., 2022). These studies have revealed that constituent assembly for production engages a left hemisphere network, with the posterior LIFG and posterior parts of the left superior and middle temporal gyri (LpSTG-MTG) as the syntactic hubs of this network (Matchin and Hickok, 2020). While the LpSTG-MTG region is more consistently associated with verb argument structure (Thompson et al., 2010; Malyutina and den Ouden, 2017), across these production studies, the LIFG is shown to be specifically involved in linear assembly of linguistic elements. As alluded to in earlier sections of this paper, this role of LIFG in constituent assembly is relevant not only because it is the most consistently lesioned region in PSA-G (den Ouden et al., 2019), but is also the end-stage hub for the highly coordinated encoding of lexical, morphosyntactic, and phonological representations for different elements in the sentence (Sahin et al., 2009; see also Zhu et al., 2022).

In summary, several lines of evidence indicate that constituent assembly is a computationally demanding process that proceeds incrementally, hinges on verb retrieval, and engages morphological elaboration only after selection of the lexical head. Production trade-offs between syntactic and lexical complexity indicate that fluent sentence production depends on a precisely timed, synergistic coordination between morphosyntactic, lexical (verb), and phonomotor processes. The LIFG is a critical end-stage hub for this integration between constituent assembly and phonomotor encoding.

TABLE 2 Definitions of key terms in the Synergistic Processing Bottleneck model.

Synergy refers to the time-sensitive coordination between content (lexical processes) and structure (morphosyntactic processes) that feeds into articulatory planning for sentence production.
Processing capacity is the ability to store, compute, and update linguistic information. It is the collective outcome of lesion, cognitive-linguistic abilities, and personal factors for a person.
Processing load is the momentary effect of accessibility and task demands on language production. Several factors modulate processing load at a given moment, including language specific usage patterns and contextual accessibility.
Processing bottleneck is the outcome of handling a computation with high processing load that exceeds the processing capacity of the person. The processing bottleneck threshold depends on neurological status, particularly LIFG lesion.
Delay refers to either insufficient activation from degraded representations, slow activation, fast decay, or difficulty in resolving competition.
Phonomotor ability collectively refers to two post-syntactic processes which are not straightforward to distinguish in aphasia, phonological encoding (syllabification) and speech motor planning.

The Synergistic Processing Bottleneck model

With the aim of moving the field forward, this section outlines a multicomponent mechanistic model of PSA-G. This model integrates the core morphosyntactic deficit of PSA-G with two non-syntactic components (which admittedly are not mutually exclusive): (a) other linguistic processes inherent in sentence planning (e.g., lexical/phonomotor) and (b) processing capacity. This model is adapted from classic psycholinguistic models of language production in neurotypical speakers (e.g., Bock and Levelt, 1994; Slevc, 2023). Like classic models, this model emphasizes that language production requires a synergistic coordination between content (lexical processes) and structure (morphosyntactic processes). The difference between this model and classic models of language production is that it identifies

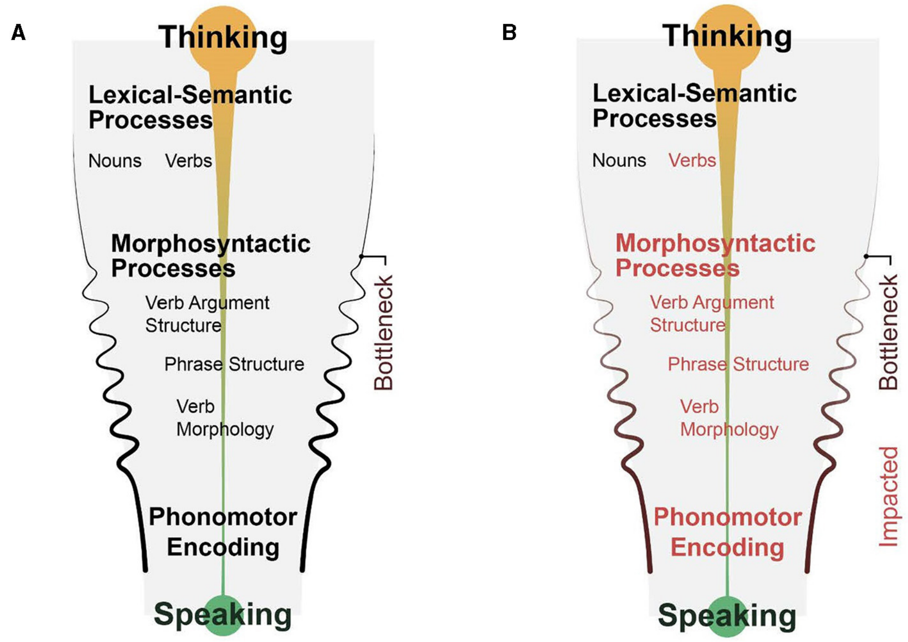

FIGURE 6
The *Synergistic Processing Bottleneck Model of Agrammatism*, showing sentence production in **(A)** neurotypical speakers, and **(B)** persons with agrammatic aphasia. Morphosyntactic computations (or constituent assembly) are a potential bottleneck due to the high processing load. Computations that are vulnerable in PSA-G due to LIFG lesion are noted in red font. These vulnerabilities exaggerate the processing bottleneck and result in slowly uttered, agrammatic speech output.

constituent assembly as the locus of a processing bottleneck for sentence planning (for all speakers). This is illustrated in Figure 6A. The central tenet of the Synergistic Processing Bottleneck (SPB) Model is that sentence production in PSA-G is undermined by a combination of delays in three linguistic processes (constituent assembly, verb activation, phonomotor planning) and processing limitations that cumulatively create a bottleneck at the point of articulatory planning. This is illustrated in Figure 6B. Key terms in the SPB model are defined in Table 2. In light of the core requirements of a future theory of PSA-G listed earlier, the SPB model differs from previous theories (Table 1) in several ways. First, it integrates empirical findings of constituent assembly in neurotypical speakers with PSA-G symptoms to identify a mechanism that can explain the relative impairment and sparing of morphosyntactic abilities in PSA-G. Second, rather than an exclusive syntactic deficit, it proposes a broader view of PSA-G that allows for the co-occurrence of non-syntactic symptoms such as non-fluency. Third, it identifies delays in the timecourse of syntactic and phonomotor processes and processing capacity limitations as the key mechanisms underlying PSA-G. Fourth, it explains symptom variability, particularly intra-person variability in PSA-G, as an interaction between processing capacity and processing load. Yet another difference between prior theories and SPB is the latter's inclusion of a neuroanatomical locus (LIFG). Finally, it provides a mechanism for differentiating the symptoms of PSA-G from non-agrammatic PSA. In the following paragraphs, the rationale for the model will be postulated. Next, PSA-G and non-agrammatic PSA will be contrasted to explain why sentence production deficits are predominant in the former, and testable predictions of the model will be outlined. I will end with implications for future research.

Comorbidity of LIFG functions provides a mechanism for the full symptom cluster

The starting point for SPB is the juxtaposition of three LIFG functions that are compromised in PSA-G due to LIFG lesions: constituent assembly, phonomotor planning, and the endstage hub for the highly coordinated encoding of lexical, morphosyntactic, and phonological representations for different elements in the sentence (Sahin et al., 2009; see also Zhu et al., 2022). As for the major lexical categories (nouns and verbs), there is evidence that verb processing selectively engages the LIFG while both nouns and verbs engage left posterior temporal regions (Shapiro et al., 2006; Faroqi-Shah et al., 2018). This explains the IFG's role in integrating linguistic and cognitive representations is also noted in other recent models (Roger et al., 2022). PSA-G is proposed to result from the cumulative effect of LIFG lesions on these three functions. While there is evidence indicating that agrammatic language co-occurs, and is even confounded by, phonomotor difficulties, there is no evidence to date indicating that the morphosyntactic deficits of PSA-G occur in isolation without any other linguistic deficits. In the absence of such evidence, it is better not to view PSA-G as an insular morphosyntactic deficit (see also Fedorenko et al., 2022). With this neuroanatomical backdrop, I will next focus on the cognitive-behavioral mechanisms underlying PSA-G.

Delays and cumulative bottleneck

We speak at an incredibly fast pace of about 150–200 words per minute (Picheny et al., 1986). To achieve this, constituent assembly requires precise synchrony between lexical retrieval and morphosyntactic processes. The encoded sentence constituents are incrementally dispatched for motor planning. The importance of timing for sentence production was first proposed by Kolk (1995). Based on the notion that syntactic trees are built incrementally for sentence production, Kolk (1995) highlighted that synchronized timing of lexical and morphological elements is essential for assembling syntactic trees. Delays in activation of lexical and/or morphological elements could result in agrammatic sentence production. In the SPB model, *delay* refers to either insufficient activation from degraded representations (Grober, 1984), slow activation (Zurif et al., 1993; Burkhardt et al., 2008), fast decay (Faroqi-Shah et al., 2010), or difficulty in resolving competition (Novick et al., 2010; Mailend et al., 2019) among lexical and/or morphological elements. Although we expect general processing speed delays in all PSA (Faroqi-Shah and Gehman, 2021; Yoo et al., 2022), there is evidence that individuals with PSA-G are particularly slow in real-time activation of lexical and syntactic representations (Freiderici and Kilborn, 1989; Prather et al., 1992, 1997; Zurif et al., 1993; Blumstein and Milberg, 2000; Burkhardt et al., 2008; Love et al., 2008; Ferrill et al., 2012). For example, in a series of studies that compared the timecourse of priming effects in PSA-G and Wernicke's aphasia, Zurif et al. (1993) found slowed activation of lexical and syntactic elements in PSA-G. In contrast, individuals with Wernicke's aphasia demonstrated a normal timecourse of lexical and syntactic activation (Prather et al., 1992, 1997; Zurif et al., 1993). A few authors have implicated a downstream effect of slowed lexical activation on syntactic structure building impairment in PSA-G (e.g., Love et al., 2008; Ferrill et al., 2012) and a few others have identified constituent assembly (Merge) as the locus of slowed activation (e.g., Burkhardt et al., 2008). Another source of activation delays is co-morbid apraxia of speech, which is attributed to delays in resolving competition between motor plans and syllable planning (Haley and Jacks, 2019; Mailend et al., 2019, 2021). The cumulative result of these different delays is an articulatory bottleneck due to which fragmented utterances are spoken slowly (Figure 6B). This is supported by the strong association between speaking rate and syntactic productivity in aphasia (Nozari and Faroqi-Shah, 2017; Faroqi-Shah et al., 2022b; Salis and DeDe, 2022).

Additionally, it is possible that the delays themselves are a circular issue where lexical, morphosyntactic, or motoric representations can decay from the short-term memory buffer before they are integrated. For example, if there is a delay in verb retrieval, the already activated verb's argument(s) may decay before the verb can be integrated with the arguments. Consistent with this, persons with Broca's aphasia use a more restricted variety of verb argument structures than other PSA (Malyutina and den Ouden, 2017). Using eye-tracking methods, PSA-G were also noted to have delayed activation of VAS (Mack et al., 2013). Likewise, there could be delays or decay of referential aspects of a speaker's message (often conveyed by pronouns, functional morphemes, or clausal structures) before constituent assembly is complete. This could account for the pervasive difficulty in expressing and comprehending verb tense morphology in PSA-G (Faroqi-Shah and Dickey, 2009).

The cumulative nature of the articulatory bottleneck implies that articulatory planning of successfully retrieved lexical elements (e.g., nouns) will be uninterrupted in PSA-G. Evidence for this comes from the finding that phonological primes did not facilitate noun picture naming but facilitated verb picture naming in a group of PSA-G who showed a selective verb deficit (Lee and Thompson, 2011a). Noun naming speed was not boosted by phonological primes because nouns did not encounter planning bottlenecks.

Processing trade-offs

A comprehensive theory of PSA-G should be able to account for the well-observed inter and intra person variability in agrammatic symptoms. Individuals with PSA vary in their processing capacity (Murray, 2012; Ivanova and Hallowell, 2014; Faroqi-Shah et al., 2022a). In this paper, *processing capacity* is defined as the ability to store, compute, and update linguistic information. It is the collective outcome of lesion, cognitive-linguistic abilities, and personal factors for any given person (Figure 1). Thus, inter-person variability could be explained by individual differences in processing capacity. Evidence suggests that those with LIFG lesions are particularly vulnerable to processing capacity limitations for language computations (Novick et al., 2010; Robinson et al., 2010; Slevc and Martin, 2016; Stampacchia et al., 2018). For example, Robinson et al. (2010) demonstrated that sentence generation became increasingly difficult for individuals with LIFG lesions as the number of conceptual propositions was increased. This relationship was not found in individuals whose lesions spared the LIFG, showing that LIFG lesions limit processing capacity. Comparable reductions in processing capacity following LIFG lesions have been reported for both linguistic and non-linguistic computations (see also Tettamanti and Weniger, 2006; Stampacchia et al., 2018).

Processing capacity can be viewed as a static ability which interacts with dynamic modulations in processing load for the speaking task at hand. This paper defines *processing load* as the momentary effect of accessibility and task demands. Several factors modulate processing load at a given moment, including language specific usage patterns and contextual accessibility (Menn and Obler, 1990; Bates et al., 1991; McRae et al., 1997; Gahl and Menn, 2016; Lee, 2020; Goldberg and Ferreira, 2022). Thus for example, planning a sentence with a typical verb-argument (e.g., *The policeman arrested the thief*) requires fewer processing resources than with a less typical argument (e.g., *The policeman arrested the teacher*), which in turn would demand fewer resources than a non-canonical sentence structure (e.g., *The teacher was arrested by the policeman*). These load effects, however, may be reversed if the context favors the less typical argument, or a non-canonical sentence frame, or with task demands. These momentary variations in processing load will affect the speed with which computations can be completed, which in turn, can exacerbate or alleviate the articulatory bottleneck. The likelihood of a processing bottleneck specifically in PSA-G is supported by the finding that non-fluent PSA's production of well-formed sentences is more accurate and faster when using more frequent subject nouns compared to less frequent subject nouns (see also Robinson et al., 2010; Speer and Wilshire, 2013). In contrast, fluent PSA do not show a facilitation of sentence structure based on subject noun frequency. Thus, task-related intra-person variability in sentence production is captured by processing load effects. Overuse of canonical word order, frozen phrases, and frequent verb forms (Bates et al., 1987; Faroqi-Shah and Thompson, 2004; Ishkhanyan et al., 2017) could be a strategy to deal with processing limitations.

Several authors have proposed processing accounts for PSA, including those for comprehension (Caplan et al., 2007; Burkhardt et al., 2008; Avrutin and Baauw, 2013), production (Kolk, 1995; Dyson et al., 2022), and overall symptoms (Hula and McNeil, 2008). The SPB model proposes that when the aggregate of a person's processing capacity and processing load during sentence production falls below a threshold, it results in agrammatic language production. The computational demands of constituent assembly trip up the sentence production machinery in PSA-G. The SPB framework thus accommodates inter- and intra-individual variability in sentence production. The SPB model differs from previous processing capacity accounts of PSA-G (Kolk, 1995; Kok et al., 2007; Caplan et al., 2013) by identifying specific syntactic and non-syntactic vulnerabilities, incorporating LIFG symptoms, including a timing component, and embracing the heterogeneity inherent in PSA-G.

Key differences between PSA-G and PSA-LS

The language sample below lucidly conveys that fluent sentences can be produced when speakers experience lexical failures. It was spoken at a rate of 140 words/minute (i.e., within normal limits) by a person with a clinical profile of Wernicke's aphasia (per the WAB-R, Kertesz, 2006). She is describing the picnic picture scene that is part of the WAB-R. The transcriber's notes are in square brackets.

> *"Okay. That will be, um, see here weeding, whiting, reading [weeding, whiting = target approximations to reading]. The cat [=dog]...is eating here, back packing [=picnicking?] and he's speaking at a ball [=target not sure, no ball in the picture]. He's got a book he's reading here, and they've got a fly [=kite] up there and I can see they're really reading."*

In the SPB framework, PSA with lexico-semantic deficits (PSA-LS) are expected to show lexical retrieval and phonological delays and difficulties, particularly for nouns. However, their preserved LIFG, their relatively spared morphosyntactic and motor abilities, and adequate linguistic processing capacity allow them to avoid an end-stage processing bottleneck in sentence production. This results in fluent sentence production that is mostly grammatically well-formed although the sentences may contain lexical errors and paragrammatisms. Self-monitoring appears to be a vulnerability that is unique to severe PSA-LS (Sampson and Faroqi-Shah, 2011).

Summary and predictions of the SPB

The SPB model is a mechanistic model of sentence production that uses the neurotypical language production framework (Figure 6A) to identify key vulnerabilities in PSA-G (Figure 6B). The SPB model accounts for the broad symptom cluster of PSA-G in the following way. LIFG lesions impair constituent assembly, verb activation, phonomotor planning, and processing capacity. In PSA-G, constituent assembly and phonomotor encoding unfold over a delayed timecourse compared to persons without LIFG lesions. The reduced processing capacity particularly impacts constituent assembly, which is a computationally demanding process that proceeds incrementally. As a result, sentences may be fragmented, and verb argument structure may be incomplete. Neurotypical findings of constituent assembly explain why verb retrieval impairments in aphasia affect sentence formulation (Antón-Méndez, 2020) and the realization of grammatical morphemes that need a lexical head (Lange et al., 2017; Boye and Bastiaanse, 2018). Grammatical morphemes that convey referential aspects of a speaker's message (e.g., verb tense; Bastiaanse and Thompson, 2012; Fyndanis et al., 2012) are additionally vulnerable from the slow timecourse of sentence planning. The interplay between reduced processing capacity resulting from LIFG lesions and processing load demands of the sentence being produced explains a variety of phenomena reported in PSA-G. First, it explains PSA-G's relatively preserved performance for some morphosyntactic computations such as incremental sentence planning, subject-verb agreement, function assignment, and grammaticality judgement (e.g., Clahsen and Ali, 2009; Lee et al., 2015). Secondly, it provides a mechanism for performance variability based on task demands or stimulus manipulations, such as structural priming (Faroqi-Shah and Thompson, 2003; Cho-Reyes et al., 2016). Third, the overuse of frequent structural and morphological elements occurs due to the lower processing demands of accessible sentence structures (Bates et al., 1991; Centeno et al., 1996; Ishkhanyan et al., 2017). Fourth, processing capacity limitations explain trade-offs between linguistic features such as between morphological and phonological complexity (Obler et al., 1999; Faroqi-Shah et al., 2010) and syntactic and semantic complexity of verbs (Thorne and Faroqi-Shah, 2016). This view of morphosyntactic planning on a processing continuum also accommodates the continuous nature of morphosyntactic ability in aphasia and reports of simplified sentence structure in other aphasia subtypes (Saffran et al., 1989; Edwards, 1998).

The SPB model provides an empirically testable framework for future investigations of PSA-G. The key predictions are outlined here, beginning with three mechanistic predictions and followed by three expectations pertaining to the pattern of linguistic deficits.

First, given the LIFG's role as the end-stage hub for integrating the incrementally unfolding lexical, syntactic, and phonological representations, the SPB model underscores the observation that there is no evidence (as yet) of a complete and isolated morphosyntactic deficit that impacts all aspects of morphosyntax with the sparing of other linguistic process (e.g., lexical-semantic). In other words, persons with PSA-G (from LIFG lesions) will also have at least some level of phonomotor and lexical deficits, the latter will be particularly evident for verbs (e.g., Miceli et al., 1988).

Second, relative to PSA-LS, PSA-G will show a delayed timecourse for morphosyntactic, verb, and phonomotor planning (Prather et al., 1992, 1997; Burkhardt et al., 2008; Mack et al., 2013). The delayed timecourse will be evident in online paradigms such as priming with different stimulus-onset asynchronies, eye-tracking, and neurophysiological responses using electroencephalography and magnetoencephalography.

Third, while we expect all PSA to show a reduced processing capacity relative to neurotypical speakers (Hula and McNeil, 2008; Caplan, 2012), processing capacity reductions will be steeper in PSA-G relative to PSA-LS, and will interact with processing load manipulations (e.g., Ivanova and Hallowell, 2014). Further, compared to other PSA, PSA-G will show larger benefits (in planning constituents, verbs, and phonomotor details) from manipulations that over-rule processing load, such as priming and usage frequency (Lee and Thompson, 2011a; Speer and Wilshire, 2013; Cho-Reyes et al., 2016; Boye et al., 2023).

The next three predictions are portrayed in the results of the path analysis in Figure 4. An "articulatory bottleneck" will be evident in the speaking rate and disfluencies of PSA-G. The relationship between non-fluency and constituent assembly will be stronger in PSA-G compared to PSA-LS, as shown in Figure 5 (Faroqi-Shah et al., 2022b). It should be noted that the non-fluency-constituent assembly connection does not preclude agrammatic output from showing up in the written modality. This is because processing capacity limitations and activation delays will still impact constituent assembly in writing tasks.

The fifth prediction is a challenge with activating verb representations and fulfilling VAS in PSA-G, which will be evident in online paradigms (Faroqi-Shah et al., 2010; Mack et al., 2013) as well as narrative language (Malyutina and den Ouden, 2017; see also Figure 4). Similar to the prediction for non-fluency, the relationship between verb activation and constituent assembly will be stronger for PSA-G compared to PSA-LS.

Finally, the vulnerability of grammatical morphology will interact with the verb deficit and show processing load effects. When a verb is a lexical head for a grammatical morpheme (as in tense marking on verbs in English), any delays or degradation of verb activation will have a downstream effect on the retrieval and planning of the associated grammatical morpheme(s). Processing load effects in the production of grammatical morphology will include trade-offs with phonological and syntactic complexity and usage frequency effects (Obler et al., 1999; Faroqi-Shah and Thompson, 2004).

The totality of the SPB model markedly differs from prior PSA-G theories (Table 1). As stated earlier, there is some intersection with other theories. These overlapping elements between SPB and a few other theories are contrasted in Table 3.

Implications for future research

The SPB model was developed from an integration of empirical findings of neurotypical and agrammatic sentence production. Thus, it is only as good as the data it was derived from. Some details of the SPB model are yet to be developed. As detailed earlier, characterization of PSA-G is somewhat murky not only from issues related to empirical rigor, but also from a disproportionate focus on syntactic theory at the cost of uncovering underlying mechanisms. To move forward, it is crucial to test the predictions of the SPB model outlined in the previous section as well as to fill in gaps where findings are inconsistent or insufficient. Here I highlight some unresolved questions and provide suggestions for the conduct of PSA-G research.

Unresolved questions

Much is unknown about the neurocognitive dynamics of sentence production in neurotypical speakers. Improved future understanding of the neurotypical mechanisms underlying sentence production can be used to further refine the SPB model. Empirical evidence in support of slow timing in PSA-G primarily comes from comprehension or lexical priming tasks (Freiderici and Kilborn, 1989; Prather et al., 1992; Burkhardt et al., 2008; Love et al., 2008). This needs to be tested and validated for speech production. Recent studies linking speech timing with morphosyntactic production in aphasia (Nozari and Faroqi-Shah, 2017; Faroqi-Shah et al., 2022b; Salis and DeDe, 2022) are the first step forward in empirically showing a connection between syntactic planning and time cost. While processing capacity limitations are demonstrated in individuals with LIFG damage, we lack an understanding of the aphasia deficit profile of these individuals. Future research can verify and complete the triangular relationship between delayed activation, processing limitations and PSA-G. Given the central role of verbs in sentence construction, we need to resolve some of the inconsistencies in verb deficits in PSA-G (Matzig et al., 2009), particularly in explicating their time course of activation and VAS elaboration. The SPB model does not address how LIFG damage affects the role of the temporal lobe syntactic hub (Fedorenko et al., 2018; Matchin and Hickok, 2020) and the functional connectivity between these two hubs. We currently lack exact knowledge of which factors are mediators, confounds, and moderators of language production in PSA-G, thus limiting our understanding of underlying mechanisms and individual differences. In sum, we hope that researchers can use the SPB model to spur future research that moves away from the syntax-centric view of PSA-G.

Guidelines for experimental rigor

Methodological rigor and replicability are the foundations of science. The issues of empirical rigor pertaining to PSA-G research were noted in an earlier section and were based on the key shortcomings noted in Faroqi-Shah (2020) scoping review of agrammatism research. It is not clear if some of the same empirical issues exist (or do not exist) in research on other topics in aphasiology. The following recommendations focus on participant description and addressing methodological confounds in PSA-G research that were noted by Faroqi-Shah (2020) and may (or may not) be applicable to aphasiology in general. These guidelines do not cover statistical treatment of data (e.g., Bezeau and Graves, 2001).

1. *Etiology*. First and foremost, aphasia is a health condition that arises from a medical etiology. Details about the etiology

TABLE 3 The relationship between extant theories of agrammatism and the Synergistic Processing Bottleneck (SPB) model.

SPB predictions	Examples of related theories	Difference(s) with SPB
Persons with PSA-G will not show an isolated morphosyntactic deficit, but additional deficits in processing capacity and phonomotor planning resulting from LIFG lesion	Phonological Simplification (Kean, 1977) results in omission of bound morphemes	SPB implicates both phonological and motor planning ("phonomotor") vulnerabilities; the totality of morphosyntactic and phonomotor processing demands shape utterance well-formedness
Relative to PSA-LS, PSA-G will show a delayed timecourse for morphosyntactic, verb, and phonomotor planning	Time-based approaches (Friederici, 1995; Kolk, 1995; Swinney and Zurif, 1995) suggest that slowed activation (or fast decay) of lexical representations affects syntactic structure building, or that constituent assembly is slowed (Burkhardt et al., 2008). While most theories focus on comprehension, Kolk (1995) addresses both comprehension and production	SPB is production-focused; specifies three processes that are susceptible to delays; proposes a resultant cumulative bottleneck at the point of articulatory planning; and is more explicit about differences between aphasia subtypes
Processing capacity reductions will be steeper in PSA-G relative to PSA-LS, and will interact with processing load manipulations	Economy of effort (Pick, 1913), Division of labor (Gordon and Dell, 2003), Processability theory (Dyson et al., 2022), Rational behavior (Fedorenko et al., 2022); these theories either directly or indirectly imply processing limitations in PSA-G; and accommodate utterance-level differences in processing costs	SPB more explicitly differentiates processing capacity (static ability) from processing load (momentary); identifies specific instances and behaviors associated with processing limitations
An "articulatory bottleneck" will be evident in the speaking rate and disfluencies of PSA-G	none	
Difficulty with activating verb representations and fulfilling verb argument structure (VAS)	Argument Structure Complexity Hypothesis (Thompson, 2003) proposes difficulties in accessing verbs for production according to VAS hierarchy	VAS is one of many linguistic variables that affect processing load; greater emphasis is placed on uncoordinated timing of verb and VAS elements
The vulnerability of grammatical morphology will interact with the verb deficit and show processing load effects	Theories of verb tense (Friedmann and Grodzinsky, 1997; Burchert et al., 2005; Faroqi-Shah and Thompson, 2007; Bastiaanse and Thompson, 2012; Fyndanis et al., 2012) and closed class morphology (Bradley et al., 1980; Boye and Bastiaanse, 2018); these theories identify difficulties with specific types of morphemes	Grammatical morphology is viewed within the broader context of constituent assembly; its dependence on retrieval of lexical heads and usage-frequency affects its accessibility

(e.g., type, number, location of strokes), time-post onset, and specifically, diagnosis of aphasia should be provided for participants in empirical studies.

Diagnosis of PSA-G. An accurate diagnosis of agrammatism allows for replication and cross-language comparisons. It is important to operationally define and characterize the agrammatic impairment in study participants for internal validity as well as generalizability of findings. While physicians may diagnose aphasia, the characterization of speech-language behavior lies mainly within the scope of practice of speech-language pathologists (American Speech-Language-Hearing Association, 2016). In countries where the SLP profession does not exist, researchers could operationally define their understanding of PSA-G for their language (see Menn and Obler, 1990) and provide supplementary qualitative details, such as language samples. Researchers should document the diagnostic process, including the standardized assessments administered by a licensed SLP, and criteria used to determine the presence (vs. absence) of PSA-G. Researchers may also consider using the core outcome dataset for aphasia recommended by the ROMA consensus (Research Outcome Measurement in Aphasia, Wallace et al., 2019).

2. *Language Sample Analysis (LSA).* Diagnosis of PSA-G should be supported by a LSA, which refers to quantitative measures derived from narrative language. LSA is more ecologically valid than constrained sentence tasks, it has been conventionally used to document language characteristics in clinical populations (MacWhinney et al., 2011), and is particularly useful in documenting the core morphosyntactic features of PSA-G. In PSA-G research, narratives have been typically elicited from descriptions of picture scenarios such as the "Cookie theft picture" (Goodglass et al., 2001), re-telling of the "Cinderella" (or "Red Riding Hood") story, and elicitation of a personal narrative such as their "stroke story" (Edwards, 1998; Rochon et al., 2000; MacWhinney et al., 2011; Hsu and Thompson, 2018). A minimum of a 150-word language sample has been recommended for LSA (Saffran et al., 1989). While some studies have provided comparisons of quantitative measures between PSA-G and neurotypical adults (Rochon et al., 2000; Hsu and Thompson, 2018), studies that provide agrammatic vs. non-agrammatic aphasic comparisons are particularly helpful in diagnosing PSA-G (Saffran et al., 1989; Faroqi-Shah, 2020; see also Mack et al., 2021 for primary progressive aphasia). Faroqi-Shah (2020) examined the diagnostic accuracy of various measures derived from the tools available at Talkbank (https://aphasia.talkbank.org/, MacWhinney et al., 2011), identified five core measures that differentiated PSA-G from non-agrammatic aphasia with 89% classification accuracy, and provided cut-off scores. Given the intensive time commitment for LSA, at minimum, perceptual ratings of narrative language could be provided. Casilio et al. (2019) developed a 27-item perceptual rating scale for narrative language in aphasia and identified four items in this scale clustered together and marked agrammatic behavior.

As noted at several instances in this paper, it is worth considering morphosyntactic production impairment in PSA on a continuum rather than a categorical diagnosis, especially depending on the research questions. Given the limitations in sentence production imposed by lexical deficits (e.g., Berndt et al., 1997a; Faroqi-Shah and Thompson, 2003; Speer and Wilshire, 2013), it is important for a continuous measure of morphosyntactic ability to consider the confound of lexical abilities. Thorne and Faroqi-Shah (2016) addressed this by calculating a difference score (the Standardized Syntax Semantics Difference Score, SSSD) based on morphosyntactic and lexical productivity. Participants were then categorized into those with predominantly morphosyntactic (PSA-G) or lexico-semantic (PSA-LS) deficits (see also Faroqi-Shah et al., 2022a).

3. *Comparison groups.* The rigor of characterizing PSA-G will be enhanced by striving for double dissociations by including an *aphasic* non-agrammatic comparison group. As noted earlier, it is crucial to provide details of the linguistic and clinical characteristics of this comparison group, including procedures for matching groups.
4. *Mediating, moderating, and confounding variables.* It is important to document non-linguistic mediating and moderating variables, particularly, an oro-motor examination for co-morbid speech conditions (Ziegler et al., 2022). It is also important to provide a cognitive profile with aphasia-friendly assessments that address the verbal limitations of the participant (e.g., Ivanova and Hallowell, 2014; Faroqi-Shah et al., 2022b). Sensory screenings should be conducted and reported, depending on the experimental demands (hearing, vision, color vision, field cuts). Motor abilities, particularly, with reference to hand-use if any keyboard, writing, or gesturing response is used. Authors should document language moderators such as bilingual status, literacy/education, and word retrieval scores.
5. *Experimental accommodations for aphasia.* Details of experimental manipulations that are unique to aphasia must be provided. For example, did any participants have hemiparesis that might have affected their keyboard responses (if used), which hand was used for responding, were verbal instructions supplemented by written instructions, how was comprehension of task instructions determined, what was the protocol for practice items, etc.

In summary, research methods that consider the multidimensional nature of aphasia will yield a more accurate picture of PSA-G and help advance the field.

Conclusion

Following a critical examination of current evidence on PSA-G, this paper questions the assumption of the existence of an insular morphosyntactic deficit in PSA. Instead, this paper proposes a broader view of PSA-G as a cluster of morphosyntactic and phonomotor deficits arising from LIFG damage. The LIFG is the hub for synergistically coordinating message content with structure. Structure building (constituent assembly) is computationally demanding and can stall fluent speech output (articulatory bottleneck), especially in persons with limited processing capacity. The SPB model attempts to provide a comprehensive account of PSA-G and can be fine-tuned with future evidence.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Three conceptual clarifications about syntax and the brain

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Linguistic theories offer empirical hypotheses about the architecture of human language, which provide the basis for neurobiological investigations into the study of language use. Unfortunately, progress in linking the two fields of inquiry is hampered because core concepts and ideas from linguistics are not seldom misunderstood, making them controversial and seemingly irrelevant to the neurobiology of language. Here we identify three such proposals: the distinction between competence and performance, the autonomy of syntax, and the abstract nature of syntactic representations. In our view, confusion about these concepts stems from the fact that they are interpreted at a level of analysis different from the level at which they were originally described. We clarify the intended interpretation of these concepts and discuss how they might be contextualized in the cognitive neuroscience of language. By doing so, the discussion about the integration of linguistics and neurobiology of language can move toward a fruitful exploration of linking hypotheses within a multi-level theory of syntax in the brain.

KEYWORDS

computation, algorithm, implementation, linking hypothesis, autonomy of syntax

1. Introduction

Despite obvious differences in the types of research questions, methodologies and data, both linguistics and the neurobiology of language are concerned with the same object of inquiry: the nature of the human language faculty. Ideally, they should constrain each other and come to a mutual understanding of the fundamental properties of human language. A possible reason why true mutual understanding does not arise very often might be that certain core proposals put forward in linguistics are frequently misunderstood and therefore prematurely rejected in the neurobiology of language. In this paper, we discuss three examples, concerning the longstanding distinction between competence and performance, the computational autonomy of syntax, and the abstract nature of syntactic representations. We propose that mutual understanding between linguistics and neurobiology of language requires evaluating linguistic concepts and proposals at the proper level of analysis (see Poeppel et al., 2008 for a similar perspective, addressing the problem of speech perception). As such, we suggest that an integrated, multi-level theory of syntax can help ground the neurobiology of language in linguistic theorizing.

2. Levels of analysis

Marr (1982) famously argued that a complete description of any information-processing system involves three levels of analysis: the computational, the algorithmic, and the implementational level. The computational level is concerned with the nature of the problem being solved: what is computed, what the goals of the computations are, and what the constraints of the proposed solution are. The algorithmic level is a description of the actual processes required to solve the problem, which are defined in terms of the input and output representations and the algorithms for mapping input to output. Last, the implementational level specifies the hardware in which these processes are realized physically, for instance, in neural tissue. When proposing this tripartite framework, Marr (1982, p. 25) remarked that the "three levels are coupled, but only loosely". By this he meant that while there must be some connection between the different levels of analysis, it is not expected that the properties of any of the three levels map onto the other levels in a transparent manner.

Theoretical and neurobiological models of language both aim to explain how language is instantiated in the mind/brain, but they do so at different levels of analysis. Linguistic theories are formulated at the computational level, psycholinguistic theories of language processing are algorithmic-level theories of how linguistic knowledge is put to use, and neurobiological theories of language processing are defined at the implementational and (to some extent) algorithmic levels of analysis. Core aspects of the three proposals mentioned above—the notion of competence, autonomous syntax, and syntactic representations—are part of the computational-level theory of language. Following Marr's remark, this means that they have no straightforward implications for the neurobiological implementation of the linguistic system (Marantz, 2005; Grimaldi, 2012; Sprouse and Lau, 2013; Embick and Poeppel, 2015; Johnson, 2017). It seems to us, however, that they are nevertheless frequently understood as describing the implementational level. This assumption might be based on ontological commitments about the relationship between brain and behavior—including the localizability of cognitive functions and one-to-one mappings between cognitive functions and neural mechanisms—that are most likely incorrect and must be reconsidered in light of current neuroscientific evidence (Mehler et al., 1984; Westlin et al., 2023). A consequence of this implementational interpretation of computational-level ideas is that linguistic proposals are falsified, rejected or dismissed as not psychologically or neurobiologically "real". In our view, this state of affairs is problematic. Here, we will therefore clarify the intended meaning of the three ideas and discuss how they might be properly interpreted in the context of the neurobiology of language. The apparently paradoxical take-away of this opinion piece is that all three proposals can be both right and wrong at the same time, depending on the level of analysis at which they are evaluated (see also Francken et al., 2022).

Before moving on, we should clarify our intentions. First, we will not try to defend these three ideas. These matters have been discussed (and continue to be discussed) in the linguistic literature at length. Instead, we will introduce each idea, explain its intended scope, and, acknowledging that it is a computational-level idea, evaluate its potential implications for the neurobiology of language. To the extent that we refer to existing neuroscience research, this is not to assess whether its empirical (implementational-level) results do or do not support the (computational-level) ideas. Rather, it is to show that the research is used to evaluate the correctness of the implementational interpretation of these ideas. To foreshadow one example, consider the thesis that syntax is computationally autonomous (discussed further in Section 3.2). Instead of evaluating whether the empirical results of neuroscience research are consistent with this computational-level idea, it often happens that the results are evaluated in terms of whether they support the idea that syntax is neuroanatomically autonomous and modular. While certainly interesting and important, that is a different question, related but not identical to the original thesis. A second caveat is that the arguments in our discussion are implementation-neutral, which means that we do not take a stance here on what the right neurobiological units or mechanisms are to describe or explain brain functioning. The fact that our discussion of the language-neuroscience literature contains mostly fMRI studies is simply because the arguments we identify as problematic are most prevalent in that literature. Nevertheless, we believe that our claims are applicable to cognitive neuroscience of language at large, whatever the correct or most useful way appears to be to describe brain activity. Even if it turns out that current views on the neural foundations of cognition are completely wrong, this will not fundamentally alter our analysis.

3. Three linguistic concepts

3.1. Competence and performance

Chomsky (1965) made a distinction between competence—our knowledge of language and linguistic structures—and performance, our use of language in concrete situations. In Marr's terms, competence is a computational-level notion, describing what we can do (our intensional capacity), while performance is defined at the algorithmic level, describing what we actually do and how we do it (Hornstein, 2015). As competence and performance refer to the same cognitive system (albeit at different levels of abstraction), their theories should ultimately constrain one another. Thus, distinguishing competence from performance neither entails that a certain linguistic behavior (described by performance models) cannot inform the competence theory, nor that aspects of the competence theory do not have to be incorporated in performance models (Marantz, 2005; Neeleman and van de Koot, 2010).

Being a capacity, competence cannot be observed directly and must be reconstructed by or inferred from observations of situations in which the capacity is put to use (Francken et al., 2022). In language, competence is an idealization over a whole range of linguistic behaviors, observed through different measurement techniques (e.g., conversations, acceptability judgments, behavioral tests, brain recordings). Described as such, the distinction between competence and performance can be useful for cognitive neuroscientists, for at least two related reasons. First, observations about behavior are often misleading about the organizational principles of the underlying capacity. Like any cognitive task, linguistic behavior is guided by knowledge in its own domain, but it is not completely determined by it. Language use is fundamentally an interaction between linguistic competence and other properties of human cognition, i.e., non-linguistic factors that affect when, how, and which structure-building algorithms are applied. Performance data are therefore inherently noisy; they hide underlying consistencies and regularities and contain more information than can be explained by any theory of language. Describing the principles of the underlying capacity necessarily requires abstracting away from performance factors that are not considered inherent to that capacity.

A second, related reason is that the competence-performance distinction mirrors the way cognitive neuroscientists approach brain recordings collected in experimental settings. In the context of neurolinguistic experiments, brain states recorded on individual trials correspond to individual acts of performance (e.g., the neural correlates of individual speech acts), and the entire collection of trials within an experiment is the performance data (akin to a small language corpus). Before abstraction, the set of brain activations will be noisy, because they contain the neural correlates of the processes that build syntactic structure, of performance factors that affect the application of these processes (e.g., attention, memory, context), and random noise (e.g., participants' movements, artifacts, scanner noise).

To get closer to (the neural basis of) the underlying capacity, some sort of abstraction or idealization is necessary. Concretely, this can be performed through averaging (in univariate analyses) or through more complicated pattern detection techniques (in multivariate analyses), both of which might be seen as quantitative instantiations of abstraction. Analogous to the linguistic notion of competence as abstraction of performance, competence in neuroscience is an abstraction of brain states (see Adger, 2022). A further level of abstraction is provided by meta-analyses, which seek functional convergence across multiple experiments to remove contingent performance effects for a particular factor of interest. This approach has been used in recent meta-analytic studies on syntactic processing and modality independence, which aim to characterize linguistic competence in neural terms (Zaccarella et al., 2017b; Walenski et al., 2019; Trettenbrein et al., 2021).

3.2. Autonomy of syntax

The autonomy-of-syntax thesis holds that syntax is computationally self-contained, meaning that its primitives and combinatorics are not completely derivable from or reducible to non-syntactic factors, such as meaning or frequency of occurrence (Chomsky, 1957). The autonomy of our syntactic system underlies our ability to judge a sentence like "colorless green ideas sleep furiously" as acceptable (and distinguish it from the reverse, and unacceptable, "furiously sleep ideas green colorless"), despite it being semantically anomalous and highly infrequent. As a statement about a capacity, the autonomy thesis makes no claims about how we arrive at this judgment. When someone judges the acceptability of a given sentence, its non-syntactic properties can and do modulate the processes underlying the person's judgment—they are likely to judge faster the acceptability of the semantically coherent "revolutionary new ideas appear infrequently"—but this is entirely consistent with the autonomy of the system qua computational properties. Thus, while the *application* of syntactic computations is affected by the properties of the systems with which syntax interfaces (e.g., semantics, phonology), the computations themselves (their *form)* are autonomous (i.e., different from semantic and phonological computations; Adger, 2018).

As the autonomy thesis is stated at the computational level of analysis, it makes no direct claims about the role of syntax in sentence processing. This is relevant to emphasize because even when a cognitive system is representationally and computationally modular, in actual comprehension all sources of information will have to be integrated. The fact that syntactic rules are autonomous does not mean that syntactic constructions are processed fully autonomously (Sprouse and Lau, 2013). Likewise, by defining the properties of the syntactic system at the computational level, no claims are made about the neurobiological implementation of that system. The autonomy thesis therefore does not predict that there is an area in the brain that is uniquely responsive to syntax. Recent neuroimaging studies have shown that syntactic combinatorics are subserved by (the interaction between) specific regions in the left inferior frontal and posterior temporal lobe, perhaps partially segregated from semantics (Pallier et al., 2011; Goucha and Friederici, 2015; Zaccarella and Friederici, 2015; Zaccarella et al., 2017a; Campbell and Tyler, 2018; Zhu et al., 2022). It is important to realize, however, that if such a neural syntax-semantics dissociation were not observed, the autonomy thesis would not have been falsified (see Mehler et al., 1984; Poeppel and Embick, 2005).

That autonomy of syntax is a computational-level claim without straightforward implications for neurobiology appears to be misunderstood sometimes. For instance, Zhu and colleagues state that the autonomy (or modularity) of syntax as a computational system is challenged by recent observations that syntactic and semantic processing both activate a frontal-temporal network in the brain, and that none of the areas involved is specific for syntax or semantics (Zhu et al., 2022). Similarly, Fedorenko and colleagues have shown that all brain areas that are responsive to syntax are also responsive to words, which they claim to be inconsistent with the idea that syntactic computations are abstract and insensitive to the nature of the units being combined (Fedorenko et al., 2012, 2020; Blank et al., 2016). The idea is that the absence of a neurobiological dissociation between syntax and (lexico-)semantics in the language network suggests that there is no cognitive or functional segregation between syntax and (lexico-)semantics. Besides being challenged on empirical grounds (see e.g., the lesion data in Matchin et al., 2022), this argument is also inferentially problematic. First, it presumes that stimuli in experiments can successfully segregate syntax and semantics, such that the linguistic input to participants only contains syntax. However, this is never the case, as syntactic features clearly cannot be presented in isolation (see also Moro, 2015; Matchin, 2023). Rather, if overtly present, they are always embedded in the morphological structure of words (e.g., agreement), in the sequential structures of phrases and sentences (e.g., word order, displacement), or they are simply properties of the words themselves (e.g., word category). In other words, syntactic features can be computationally autonomous even if they are physically realized in the non-syntactic information that makes up an utterance. It is therefore not surprising that brain areas responsive to syntax are also sensitive to words. Second, the autonomy of a computational system does not necessarily imply the segregation of its neurobiological implementation. Absence of a dissociation in the brain is entirely compatible with abstract, autonomous computations.

3.2. Abstract units of representation

Syntactic generalizations are commonly defined over abstract structures, such as noun phrases (NPs) and verb phrases (VPs), or even just phrases (XPs). For a computational-level theory, this abstract level of description is necessary to reveal deep syntactic principles that amalgamate superficially disparate phenomena. To give an example, in classical X-bar theory it was proposed that all phrases (NPs, VPs, etc.) have the same asymmetric hierarchical format, in which the head of the phrase and its complement form a unit, which then combines with a specifier to form the phrasal unit (Chomsky, 1970). Only by stating this property in abstract terms, roughly corresponding to the bracket notation [$_{XP}$ YP [$_{XP}$ X ZP]] (XP, in short), is it possible to define an overarching generalization. To the extent that it captures empirical observations (e.g., about distributional patterns within and across languages), the X-bar generalization is explanatorily valuable for the computational-level theory. During language processing, however, syntactic information never appears in isolation: in externalized language, phrases are lexicalized entities, and they must be processed as such (see Section 3.2). Though the brain has to recognize that sequences like "very fond of syntax" and "totally understand the argument" are, at some level, structurally the same and therefore subject to the same restrictions, this does not mean that they are mentally or neurally represented as fully abstract XPs. Instead, they could be represented as phrase structures whose lexical and semantic information is retained, and in which syntactic information is realized through features carried by the specific lexical items. Indeed, this type of representation is consistent with the results of neuroimaging studies that have been taken to support a constructionist view of grammatical knowledge. That is, studies have found that certain syntactic constructions are neurally distinguishable by virtue of their semantic content, which would be in line with the view that that these constructions are represented as pairings between form and meaning (Allen et al., 2012; Pulvermüller et al., 2013; van Dam and Desai, 2016; Gonering and Corina, 2023). However, these findings are equally compatible with linguistic theories that postulate syntactic generalizations over abstract structures devoid of meaning. To appreciate this point, consider, as an analogy, the interpretation of structural priming effects in the psycholinguistic literature. It is well-known that structural priming effects are sensitive to lexical overlap between the prime and the target (Branigan and Pickering, 2017). This is expected on the view that phrases are mentally represented and processed in the form of lexicalized structures rather than fully abstract templates (algorithmic level), but it does not mean that the abstract syntactic generalization, in which phrase structures are underlyingly identical, is empirically incorrect (computational level).

Similarly, syntactic operations are commonly defined over categorial types. During language processing, however, they necessarily apply to tokens that are instantiations of those types. It is therefore possible that, in neurobiological terms, combining "the" and "cat" is different from combining "a" and "dog", even though in computational terms, both involve the composition of a noun phrase. Both combinatorial operations are constrained by the fact that determiners combine with nouns, and that this operation is hierarchical, binary, and compositional. On this view, the abstractness of the combinatorial operation lies not in its symbolic realization, but in the fact that the constraints on the operation are independent of the specific lexical items to which it applies. Note that this does not deny the possibility that averaging over a sufficiently large number of instances of minimal combinations between for example determiner-noun, adjective-noun or pronoun-verb will yield a reasonably specific neural activation pattern initially suggestive of abstract syntactic combinatorics (e.g., Goucha and Friederici, 2015; Zaccarella and Friederici, 2015; Zaccarella et al., 2017a; Segaert et al., 2018; Matar et al., 2021; Murphy et al., 2022). Rather, it indicates that the underlying neural populations are responsible for the compositional combinations of specific lexical items (instead of abstract variables), and that these compositions are constrained by the syntactic properties of those lexical items. We speculate that such context dependence might be the reason that it has proven difficult to isolate syntactic combinatorics in neural data—that is, because syntax is to be found in the constraints on the combinatorial operations, not in the operations themselves (see also Pylkkänen, 2019; Baggio, 2020).

4. Toward a multi-level theory of syntax in the brain

To integrate computational-level descriptions provided by linguistics with implementational-level theories in neuroscience, Marr (1982) suggested an intermediate level of description which specifies *how* the processing system can solve its computational problems—the domain of psycholinguistics. In general, mapping linguistic theories to psycholinguistic models is non-trivial, because the computational (grammatical) analysis alone underdetermines the possible (parsing) algorithms. However, the principles of computational-level theories do act as boundary conditions for models at the algorithmic level, so they should constrain our theories of language processing (Gallistel and King, 2009). That is, algorithmic theories of syntactic processing must be such that they respect the grammatical constraints defined at the computational level of syntactic competence, including constraints on representations and constraints on computations. As an example of the former, it is well-known that the semantic interpretation of phrases and sentences is derived from hierarchical structure. The implication of this result for language processing is that we can regard as deficient those algorithmic models that are unable to derive structure-dependent meanings (Coopmans et al., 2022). Regarding computations, it has been argued that structure-dependent syntactic operations, like long-distance displacement, obey locality constraints. Using this computational-level result as a boundary condition on algorithmic theories, we can conclude that models of the comprehension of filler-gap dependencies that posit gaps in island configurations are inadequate (Phillips, 2006; Chesi, 2015). Roughly corresponding to these two types of constraints (on computations and representations, respectively), we envision two ways in which the different levels of analysis could become more strongly connected in an integrated, multi-level theory of syntax in the brain.

One way to integrate linguistics and psycho-/neurolinguistics is to devise computationally explicit linking hypotheses between their levels of analysis. This is quite challenging, not only because the "parts lists" of linguistics and neuroscience are ontologically incommensurable (Poeppel and Embick, 2005; Poeppel, 2012), but also because the notion of competence is usually not formulated in a way that aligns with the requirements of real-time processing. Syntactic competence is often described as a static body of knowledge. While sentence structures are derived procedurally, and the derivations are logically ordered, the entire derivational analysis is atemporal. Hierarchical syntactic structures are commonly derived bottom-to-top, starting with the most-embedded element in the structure. Syntactic processing, instead, does take place in time, starting with the first element in the sentence regardless of its position in the hierarchical structure. To illustrate the apparent misalignment, consider a phrase like "eat the cookies", which is derived by first combining "the" and "cookies", and then combining "eat" with the phrase "the cookies". The claim that "the" and "cookies" are combined first should not be interpreted temporally; it is not inconsistent with the incremental interpretation of "eat the cookies". Thus, the logical order of syntactic derivations bears no relation to the temporal order of processing. As processing must take place in time (and derivations need not necessarily be bottom-to-top, see Phillips and Lewis, 2013 and Chesi, 2015), one way to resolve the tension would be to reformulate competence into algorithmic procedures that can be applied incrementally, in a roughly left-to-right order (Phillips, 2003; Poeppel and Embick, 2005; Sprouse and Hornstein, 2016). In this way, competence directly interacts with performance, in the sense that the former constrains the algorithmic steps that are applied. And beyond facilitating the mapping between competence and performance, there are empirical benefits of this approach as well (e.g., it can explain conflicting outcomes of certain constituency tests; Phillips, 2003).

An alternative strategy for linking levels of analysis does not involve reformulating syntactic competence but involves using the structures computed at the computational level as the ultimate goal of structure-building algorithms. In this view, syntactic derivations remain atemporal, so derivational theories of syntax should not be interpreted as theories of how mental representations are actually derived in the mind of a speaker-listener. Rather, they merely describe, in computational-level terms, the logical properties that the syntactic system must have, including constraints on the form of syntactic representations. Algorithmic theories of syntactic structure building then build only those (partial) structures that are licensed by the competence theory (in whatever way works, as there are no constraints on computations), but they do not proceed in the way dictated by the derivational analysis (see also Neeleman and van de Koot, 2010; this approach aligns with the notion of "weak competence" in Baggio, 2020). As such, there is no need for alignment between the temporal order of events in psycholinguistics and the logical orders of events in syntax. The competence theory contains an abstraction description of what the performance model does, but stays silent on how it does it.

In either case, the output of algorithmic procedures must be mapped onto neural data through implementational linking hypotheses. In neuroscience work adopting naturalistic paradigms, it is common to use surprisal or node count as the linking hypothesis (Brennan, 2016; Hale et al., 2022), but neither metric reflects an algorithmic operation (Stanojević et al., 2021; Coopmans, 2023). One type of approach that we find more promising involves Combinatory Categorial Grammars (CCGs), which have the right level of grammatical expressivity to model natural language syntax (i.e., slightly beyond context-free power). Moreover, as CCGs have flexible constituency, they afford multiple ways of algorithmically deriving structures for the same sentence (Steedman, 2000). Each of these derivations has the same compositional semantic interpretation, which is assigned and updated incrementally, making this model suited for modeling language processing. Indeed, the use of CCGs is promising on both predictive and explanatory measures of empirical success. In terms of prediction, recent naturalistic fMRI studies have shown that complexity metrics directly derived from CCG derivations improve predictive accuracy in regions of the language network above and beyond predictors derived from context-free phrase structure (Stanojević et al., 2021, 2023). With respect to explanation, a clear benefit of this algorithm-centered approach is that it yields explicit theories about the computations that must be implemented in the identified brain regions. It commonly still relies on localization of functions, but at least the functions are made explicit (Mehler et al., 1984; Poeppel, 2012; Martin, 2020; Westlin et al., 2023).

To summarize, the goal of this paper was to clarify the interpretation of three key ideas in linguistics (competence vs. performance, autonomy of syntax, and the nature of syntactic representations), in order to advance the integration of linguistic theory with the neurobiology of language. Taking a levels-of-analysis perspective, we suggest that one source of misunderstanding about these ideas is that they are interpreted at the wrong level of analysis. A multi-level approach to syntax, in which different concepts are explicitly defined and interpreted at the appropriate level, can give rise to a fruitful exploration of the linking hypotheses across levels, at the interface between linguistics and neuroscience.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, writing—original draft, and writing—review and editing: CC and EZ. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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