



ELSEVIER

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Journal of Neurolinguistics

journal homepage: www.elsevier.com/locate/jneuroling

ROSE: A neurocomputational architecture for syntax

Elliot Murphy^{a,b,*}^a Vivian L. Smith Department of Neurosurgery, McGovern Medical School, UTHealth, 1133 John Freeman Blvd, Houston, TX, 77030, USA^b Texas Institute for Restorative Neurotechnologies, UTHealth, 1133 John Freeman Blvd, Houston, TX, 77030, USA

ARTICLE INFO

Keywords:

Syntax
Neural oscillations
Merge
Delta
Traveling waves

ABSTRACT

A comprehensive neural model of language must accommodate four components: representations, operations, structures and encoding. Recent intracranial research has begun to map out the feature space associated with syntactic processes, but the field lacks a unified framework that can direct invasive neural analyses. This article proposes a neurocomputational architecture for syntax, termed ROSE (Representation, Operation, Structure, Encoding). Under ROSE, the basic data structures of syntax are atomic features, types of mental representations (R), and are coded at the single-unit and ensemble level. Operations (O) transforming these units into manipulable objects accessible to subsequent structure-building levels are coded via high frequency broadband γ activity. Low frequency synchronization and cross-frequency coupling code for recursive structural inferences (S). Distinct forms of low frequency coupling encode these structures onto distinct workspaces (E). Causally connecting R to O is spike-phase/LFP coupling; connecting O to S is phase-amplitude coupling; connecting S to E are frontotemporal traveling oscillations. ROSE is reliant on neurophysiologically plausible mechanisms and provides an anatomically precise and falsifiable grounding for natural language syntax.

1. Introduction

Modern linguistics has arrived at the general assumption that the human mind/brain applies a set of syntactic rules to recursively combine linguistic units into larger objects, deriving an unbounded array of hierarchically structured expressions, with humans inferring sentence meaning based on syntactic configuration (Chomsky, 1957; Chomsky et al., 2023; Everaert et al., 2015; Hagoort, 2023; Marcolli et al., 2023; Mukherji, 2022). Despite recent claims that “there are no traits present in humans and absent in other animals that in isolation explain our species’ superior cognitive performance”, and that humans are simply “flexible cognitive allrounders” (Laland & Seed, 2021, p. 689), amongst other claims that language cannot even be given a biological account (Smit, 2022), many linguists maintain that this capacity for constructing hierarchical syntactic objects and assigning them a categorized, labeled identity is human-specific. This remains the case even if the generic facility for recursion might be shared with other species (Liao et al., 2022). Furthermore, this capacity for hierarchical recursion has been linked to human-specific cognitive superiority (Dehaene et al., 2022; Hauser & Watumull, 2017). Certain aspects of language can only be captured via the postulation of structures with relations between their elements (Everaert et al., 2015), motivating a qualitative computational distinction between human and non-human psychology.

In the theoretical domain, an emerging consensus in neuroscience is that complex behavior and cognition rely on coordinated

* Vivian L. Smith Department of Neurosurgery, McGovern Medical School, UTHealth, 1133 John Freeman Blvd, Houston, TX, 77030, USA.
E-mail address: elliott.murphy@uth.tmc.edu.

<https://doi.org/10.1016/j.jneuroling.2023.101180>

Received 20 June 2023; Received in revised form 9 October 2023; Accepted 12 November 2023

Available online 21 November 2023

0911-6044/© 2023 Elsevier Ltd. All rights reserved.

interactions between brain regions (Miller & Wilson, 2008), with phase synchronization being a major candidate for a mechanism implementing this coordination, by gating information transmission (Bressler & Kelso, 2001) (see Appendix for Glossary of Terms). Yet, unlike for models of attention and working memory, there is a current absence of oscillatory phase coding in models of natural language.

In the empirical domain, invasive intracranial recordings have recently mapped out some of the feature space associated with 'how much' phonological information can be transmitted by different neural mechanisms (Bhaya-Grossman & Chang, 2022; Forseth et al., 2020). Yet, within the domains of syntax and semantics, there has been less clear progress.

The central question that will occupy this article concerns whether we can begin to draw causal, mechanistic connections between theoretical linguistics and the brain sciences. This article will begin by reviewing some current accounts that map syntactic operations onto neural systems, before proposing a novel neurocomputational architecture for syntax. I will be concerned with neural computation in the sense of basic linguistic operations that begin with some initial conditions, and yield an output which follows from a definite set of rules, as opposed to, say, computational modelling. Each of the sections below will review evidence supporting the general architectural placement of each level of linguistic complexity. This work is not intended to provide a mathematically rigorous derivation of how to map a phrase of complexity P onto a neural mechanism Q , since this would be much too ambitious given current knowledge. Instead, my aim is to provide a framework that will be useful for directing electrophysiological analyses based on specific neural recording scales, in particular intracranial research. This article will also attempt to provide clearer answers concerning order of magnitude estimations for how much syntactic information appears to be encoded at distinct levels of neural complexity. After surveying causal evidence for this architecture, some open questions and future directions will be presented.

2. Cracking the neural code for syntax

The past decade has seen the emergence of low frequency phase coherence as a feasible index of hierarchical syntactic structure building. This measure refers to whether two or more brain regions have similar oscillatory activity based on phase consistency. This has been associated chiefly with rule-based chunking rather than morphophonological or semantic features of phrases, typically utilizing extra-cranial recording (Lu et al., 2022a, 2022b). Concurrently, recent work has examined local cortical processing with intracranial recordings, often focusing instead on high frequency power changes. This work has exposed signatures for basic linguistic operations and conceptual categories (Murphy et al., 2022b; Woolnough et al., 2022a, 2022c). How these two distinct recording scales (low frequency and high frequency dynamics) can be combined into a coherent model of natural language syntax and cortical computation has yet to be addressed. This issue of relating invasive recordings of high frequency activity to recordings of more global dynamics remains a serious obstacle towards a comprehensive neural model of language, in particular when we recognize the lack of consensus concerning how any unit of information is neurally encoded (Poeppl & Idsardi, 2022).

Neural oscillations, which this discussion will be focused on, reflect synchronized fluctuations in neuronal excitability and are grouped by frequency, with the most common rhythms being delta (δ : ~ 0.5 – 4 Hz), theta (θ : ~ 4 – 8 Hz), alpha (α : ~ 8 – 12 Hz), beta (β : ~ 12 – 30 Hz), low gamma (γ : ~ 30 – 60 Hz) and high gamma (60 – 200 Hz). For a comprehensive review of these bands, the reader is referred to Prystauka and Lewis (2019) and Murphy (2020a), but broadly speaking high γ activity reflects local neuronal processing (Kopell et al., 2000), whereas lower frequency activity reflects regional synchronization, with a range of differences also existing within the lower bands (e.g., α is often implicated in cortical disinhibition, and θ in learning and memory). Neural synchronization can occur via synaptic coupling of inhibitory neurons and coupling of excitatory and inhibitory neurons via feedforward and feedback loops.

One way to explore these issues is through the lens of an existing neurocomputational model of syntax (Murphy, 2020a). In this model, the combinatorial power of language is indexed via various oscillatory interactions such as forms of cross-frequency coupling; that is to say, linguistic *combination* of features is achieved via the top-down coordination of faster rhythms from slower rhythms. In Murphy (2020a), empirical and conceptual motivations are presented to defend the idea that δ - θ inter-regional phase-amplitude coupling constructs multiple sets of syntactic and semantic features, and imposes biases on how to read out the items provided by this phase code. This occurs when the phase of δ is synchronized with the amplitude of θ . δ represents supraordinate syntactic categories, and θ represents feature-bundles generated via lexical access. Phase-resetting (Harris, 2023) of this mechanism, alongside concurrent encoding/storage of its products in workspaces before a newly-generated δ - θ complex is created, permits a facility for recursive self-call. Distinct β (inferior frontal cortex) and γ sources (cross-cortical sites of conceptual storage; see below) are also coupled, respectively, with δ and θ (e.g., θ - γ phase-amplitude coupling) for syntactic prediction and conceptual binding.

Traveling oscillations will also be relevant for our discussion (Muller, 2018; Murphy, 2018; Woolnough, Forseth, et al., 2022). These are oscillations which migrate in phase coherence across the brain, whereby the spiking of neural clusters is coordinated not just across two fixed points but across an extended path. Traveling oscillations support brain connectivity and function (Zhang et al., 2018). In Murphy (2020a), δ waves cycle across left posterior temporal and inferior frontal cortices, building up the syntactic workspace as successive θ -complexes are synchronized with δ . Traveling δ waves are assumed to be responsible for patterning spiking from single-to multi-unit lexical structures in each δ cycle. As such, δ would coordinate phrasal construction while θ - γ interactions would support the representational construction of linguistic feature-bundles. δ - γ coupling for featural combinatorics, a core feature of the model in Murphy (2020a), is also reproduced as a predicted mechanism for syntactic structure building in Martorell et al. (2023: 570), although these authors question the hierarchical nature of syntactic representations. δ - γ coupling is involved in fluid intelligence (Gagol et al., 2018) and linguistic phrase composition via low γ activity detected with scalp EEG (Brennan & Martin, 2020), whereby δ embeds cross-cortical γ rhythms depending on the cortical areas needed for the particular task, i.e., geometric reasoning, visual processing. Murphy (2018, 2020a) proposes that δ - γ coupling may be a generic combinatorial process, joining representations from within and

across domains. Brennan and Martin (2020) discovered an increasing scale of δ - θ and δ - γ coupling beginning at the point of a word completing a single phrase, progressing into multi-phrase units, supporting the foundations of the current model. The finding of increasing θ and β activity in MEG during incremental sentence processing also supports these assumptions (Bastiaansen et al., 2010), as does the finding of increased cross-cortical θ and γ phase coherence during reading versus visual scanning (Kujala, Mäkelä, et al., 2023).

Lastly, the basic aspects of the oscillatory dynamics of language result from genetic guidance, and a confident list of candidate genes for this guidance can be posited (Murphy & Benítez-Burraco, 2018). These candidate genes map onto specific aspects of brain function, particularly onto neurotransmitter function, and through dopaminergic, GABAergic and glutamatergic synapses.

Below, this model will be expanded on in ways that help address some important recent critiques of it (e.g., Kazanina & Tavano, 2023a; Leivada, 2017; Martorell, 2021; Mondal, 2022; Mukherji, 2022; Tavano et al., 2023) pertaining to the separability of syntax from semantics, precise spatiotemporal details, the possibility that oscillations are simply ‘emergent’, the apparent non-uniqueness to humans of oscillatory binding mechanisms, and causal evidence. Reasons to focus on this model can be found via some recent empirical support for it: Dekydtspotter et al. (2023) test the model in Murphy (2020a) and find support for syntactic processing load effects in β from EEG recordings of anaphora resolution in successive *wh*-movement in native and nonnative speakers of French.

Aiding with initial direction, Ding (2022) poses perhaps the most important question for the neurobiology of syntax: What type of neural activity, such as low-frequency activity, high γ power, or spiking rate, can track very long or very brief phrases? I will try to answer this question here in the following way, associating roughly the respective scales of recording and neurobiological organization with particular levels of linguistic complexity: low frequency activity (*structures*), high γ power (*operations*), spiking rate (*basic units/representations*).

3. Current Neural Models of Syntax

Building on past insights, new brain models of syntax should seek not only to incrementally add to existing knowledge and assumptions – they should also occasionally be “disruptive” (Kozlov, 2023; Park et al., 2023) with respect to existing pre-conceptions and disciplinary boundaries. While traditional models of working memory (e.g., Baddeley & Hitch, 1974) have been replaced by neurophysiologically sophisticated models (e.g., Lisman & Jensen, 2013), within linguistics the traditional localizationist models have yet to be supplanted in a similar way.

A comprehensive model of natural language processing in the brain must accommodate four components: *representations*, *operations*, *structures*, and their *encoding* and storage in short-term memory. Previous accounts of syntax in the brain have focused mostly, or exclusively, on only a subset of these components. For example, Friederici (2017) entertains a model of linguistic structures (S) and encoding (E), but omits details about the electrophysiological or neurophysiological basis of representations (R) and operations (O).

When summarizing previous models below, I stress that I will be evaluating these purely with respect to how they address the implementational basis of R, O, S and E. Each of these following models have great strengths with respect to how they frame various components of syntax, but my goal here is not to evaluate these models against each other. Rather, it is to address how they deal with the issue of resolving appropriate neural mechanisms for the basic computational components of syntax.

Beginning with the model in Murphy (2020a), outlined above: This took into account O and S, but there was no focus on R or how distinct components of linguistic structure are related and encoded (E).

Matchin and Hickok (2020) take into account the localization of O and S, with less emphasis on E. Nevertheless, these authors present extensive evidence to distinguish the computational roles of posterior temporal cortex (lexical-syntactic information) and inferior frontal cortex (morphosyntactic linearization).

Krauska and Lau (2022) take full consideration of the appropriate computational-level resolution for R, O, S and E, and provide a clear algorithmic-level model of syntactic processing, but the implementation-level resolution for each of these components remains unresolved.

Following the centralization of labeling in the psycholinguistics of syntax proposed in recent work (Adger, 2017; Chomsky et al., 2019; Murphy, 2015a, 2015b), Goucha et al. (2017) focus on the importance of labeling in neurolinguistic models of syntax. They keep to network-level tractographic concerns of motivating how frontotemporal regions interface to generate S and E, with no relations to R or O. Although Goucha et al. (2017) defend a clear picture of hierarchy-category relations across frontotemporal sites, the implementation of this keeps to discussion of “cross-talk” between regions, with no mechanistic details. Nevertheless, it remains well-motivated to focus on structure-building via labeling, since this operation feeds recursivity and provides a uniform account of various syntactic phenomena, such as traditional islands and locality-of-movement effects (Bošković, 2021).

The literature review in Pykkänen (2019) provides a computationally explicit depiction of the general spatiotemporal dynamics of structure/meaning inferences, taking O and S as the focal points of discussion, but to the exclusion of R and E.

Other models propose hypotheses about O and S, but the causal and mechanistic connection between these levels is not addressed. Some models that take neurophysiological details seriously nevertheless fall short with respect to fleshing out computational details for neural activity scales; e.g., in Martin (2020) γ activity is associated with “the retrieval of memory-based linguistic representations by minimal or thresholded acoustic cues” (but see Kaushik & Martin, 2022, for new directions here). What is needed is not just an account of R, O, S and E, but also a principled means to *link* these components.

Recent research has shown that the human brain and autoregressive deep language models both engage in *continuous next-word prediction* (Goldstein et al., 2022), but this literature has focused almost exclusively on single-element, lexical statistics and prediction, which many linguists would argue do not form the core basis of human language (see also Oota et al., 2022).

Empirical issues also remain. The influential claim that the basic structure-building operation MERGE “appears to be localized in a

very confined region” (Friederici & Singer, 2015, pp. 334-335), BA 44, which acts as “a combinatorial engine where words are merged together according to syntactic information” (Liu, Gao, et al., 2023) does not entirely align with direct cortical recordings (Murphy et al., 2022d) and lesion data (Matchin et al., 2020, 2022). Chronic Broca’s aphasia is associated with damage to both Broca’s and Wernicke’s areas (Fridriksson et al., 2015). Young et al. (2021) review a range of existing results from intracranial cortical stimulation mapping and show how left inferior frontal regions do indeed play a role in syntax-semantics, but likely in complex sentence processing, rather than in elementary structure-building. Relatedly, Riva et al. (2022) show how intraoperative cortical stimulation mapping implicates pars opercularis in impairments to processing sentences in passive form (‘the car was sold by Bill’), with posterior temporal cortex also being implicated in these deficits, whereas impairments to active sentences (‘Bill sold the car’) are found during posterior temporal cortex stimulation, with frontal cortex being implicated to a lesser extent, thus linking frontal cortex to complex syntactic transformations rather than basic structure-building. It also appears that persistent or severe language deficits in aphasia are common only in patients with extensive temporoparietal damage, not frontal damage (Wilson et al., 2023). Lastly, consider the findings in Desbordes et al. (2023) who used simultaneous MEG and intracranial EEG in a sentence reading Jabberwocky paradigm. These authors showed regions exhibiting word-by-word lexicality effects, progressive ramping effects over the course of the sentence, and sentence-final wrap-up effects. Though they had poor intracranial electrode coverage for STS, the authors reported that middle and posterior temporal regions showed effects for both lexicality and ramping, whereas frontal regions showed effects of ramping and sentence-final wrap-up, suggesting that initial basic syntax is executed in posterior temporal regions while later executive processes pertaining to compositional consolidation take place, grossly, in frontal cortex.

Turning to other models, Hagoort’s (2005, 2013) Memory-Unification-Control (MUC) model takes into consideration O and E, but R and S appear only via localizationist assumptions of mappings to gross anatomical regions, rather than being assembled bottom-up via specific neurophysiological mechanisms. MUC assumes that the Memory component constitutes “the only language-specific component of the model” (Hagoort, 2013), with Unification being directed by lexico-semantic properties and syntactic templates inherent to Memory. Unification is also assumed to take place in frontal cortex, however inferior frontal cortex seems to be modulated more specifically by unification demands, or the use of structure for a given task (Murphy et al., 2022d). Hagoort has qualified this stance by claiming that Broca’s area forms only the major node in the Unification network, and that it is the interactions between Broca’s area and posterior temporal cortex that are crucial (see also Baggio, 2018; Baggio & Hagoort, 2011). This opens important questions about the relative involvement (Murphy et al., 2022d), and causal involvement (Matchin, den Ouden, et al., 2022), of frontal cortex in structure-building.

With respect to models of semantics more broadly, the Controlled Semantic Cognition account (Lambon Ralph et al., 2017) is split into a representation component and a control component, for storing and manipulating semantic information during verbal and non-verbal tasks. While this provides a clear algorithmic picture for accessing and manipulating elementary semantic representations, and provides a clear localizationist topography, the model currently lacks any relation to specific levels of neurophysiological complexity. This critique also applies to the most recent reviews of the neurocomputational basis of semantic memory (Frisby et al., 2023), despite algorithmic models of semantic memory becoming more sophisticated (e.g., distinct types of contiguous or dispersed codes).

The work of Dehaene and colleagues (Dehaene et al., 2015, 2022) has perhaps come the closest to relating scales of neural activity to language. Yet, even here focus is placed mostly on R and O with no linking hypotheses between them. Under Dehaene’s framework, there are no principled delimitations as to where, and why, we would detect signatures of syntax, that might be built from independent assumptions concerning how the brain might encode basic units of information, or parse complex tree structures in real time. The frameworks in Dehaene et al. (2015, 2022) seem equally open to discovering cellular ‘barcodes’ for syntactic tree-structure composition as they are open to discovering more global signatures, which is certainly an advantageous form of experimental practice but it also renders it more difficult to motivate a specific neural architecture tying different levels of linguistic complexity together (but see Desbordes et al., 2023 for new directions mapping out the neural geometry of linguistic composition).

4. ROSE

As noted, a comprehensive explanatory account of syntax needs to accommodate *Representations* (atomic units of computation), *Operations* (manipulation and transformation of representations into a novel format), *Structures* (arrangements of representations into hierarchical relations with independent identities not reliant purely on the properties of individual units) and *Encoding* (the real-time maintenance of structures, and the ‘shielding’ of their identity to protect memoranda-specific persistent activity from decay and transformation). As such, I will defend what I will term the ROSE model.

These four components enter into any given syntactic phenomenon. We can access discrete representations without necessarily assembling a syntactic structure (as in single-word utterances), but we can also make inferences that are unique to structural configurations of language. Likewise, we can execute a basic compositional operation to generate structure, but without storing this in a memory buffer there are no mechanisms by which external cognitive systems can access this. Each component of ROSE requires the existence of the component to its left: Without atomic representations, we can execute no operations over them; without these operations, we can build no larger structures; and without a means to encode structures, we can generate no relations between elements within and across structures.

Elaborations will be provided in the following sections, but at the most elementary level I will assume that representations encompass any object manipulable by the generative component of language, being composed of features determining constraints on operations, such as selection, agreement, licensing and movement. Examples include [N], [Plural], [Dem], [C], [T], [P], and also conceptual features pertaining to lexical roots, like $\sqrt{\text{BREAK}}$ and $\sqrt{\text{HOME}}$ (Pesetsky, 1995). Syntax builds structure through recursive

applications of MERGE, and these are then entered into a space of syntactic working memory. Whereas sensorimotor systems for language production and perception require temporal information (such as prosodic structure and syllabic information), the syntactic system is only sensitive to *relations* between elements, such as various semantic features, event and quantificational structure, and hierarchical information.

Below is an outline of the basic scales of analysis that map onto each component of the model, which I will then motivate throughout the remainder of this article (see Fig. 1 for a schema of components with their associated causal/mechanistic links).

4.1. Representation-operation-structure-encoding (ROSE)

R: Single-unit encoding of conceptual features and formal syntactic features. This level involves a cellular barcode for distinct features that compose into syntactic objects coherently bound by high γ at O. It also involves vector codes for ensembles hosting features common to objects represented at O and that are ultimately coordinated by S.

O: High γ sensorimotor transformations into lexicalized objects (core network nodes: mid-fusiform cortex, orbitofrontal cortex, middle temporal gyrus, inferior frontal cortex, intraparietal sulcus) accessible to δ/θ phase-locking. This level can implement the semantic composition of language-specific concepts (minimal phrase schemes) that coordinate the firing of R units. High γ activates assemblies of distinct units hosting the barcode or vector code for units $R_1 \dots R_n$ that compose into feature-bundles.

S: A low frequency neural program for generating structural inferences over O. $\delta-\theta$ phase-amplitude coupling (posterior superior temporal sulcus to inferior frontal gyrus) for categorial inferences modulating the representation of feature-bundles in $\theta-\gamma$ by structuring the read-out of these complexes (frontotemporal language sites to cross-modular hubs).

E: Local and global workspaces for bottom-up lexical memory and top-down hierarchical memory. Traveling waves implement $\delta-\theta$ coupling for hierarchical memory, and $\theta-\gamma$ coupling for lexical memory. α power codes for workspace ‘disruption’ (posterior temporal and inferior frontal cortex). β power coding for syntactic predictions (inferior frontal cortex).

Under ROSE, high γ activity reflects operations like lexical selection from a set in Broca’s area, or orthographic-to-phonological conversions in inferior parietal cortices – core operations of language and its interfaces, but these do not appear to directly index units of computation (R).

Some researchers will claim that the brain does not recognize constructs like ‘tense’ or ‘pronominal binding’ because they cannot detect a signature of these constructs at a particular resolution. However, many such anxieties and issues with current models of language in the brain can be overcome if we more carefully entertain appropriate scales of neural complexity and signal processing. Instead of viewing each component of the model separately, successive levels of syntactic composition under ROSE follow mechanistically from the next, constituting a full-scale model with principled and falsifiable (Kleiner & Hoel, 2021) connections. The most advanced neurocomputational models of language processing (reviewed in Hale et al., 2022) rely on decoding BOLD responses and scalp EEG signatures, dissociating hierarchical from lexical-related signatures across specific time windows, but there is no clear demarcation between different linguistic components with respect to their levels of neural organization. Many such models are also extensional in character, as opposed to being concerned with the operations and representations that are needed to arrive at the output of language processing (but see Brennan et al., 2020, who centralize algorithmic processes).

Other models make lexicalist distinctions between lexical node representations and higher-order structure representations in

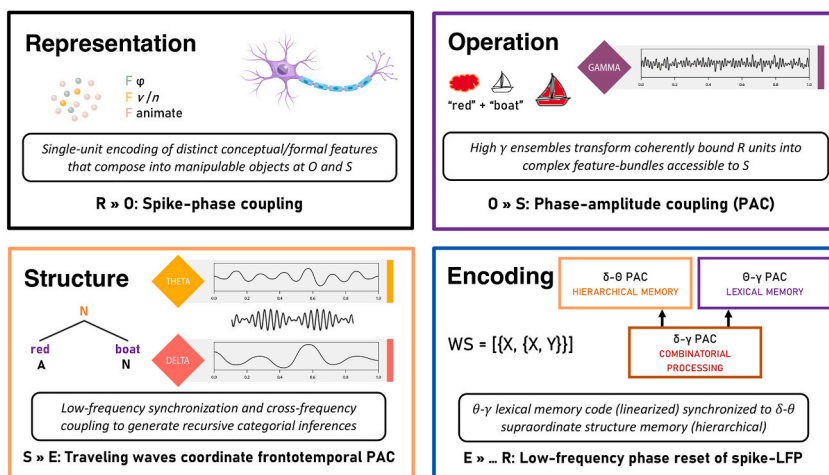


Fig. 1. Basic components of the ROSE model. Each box contains a graphical depiction of the relevant organizational scale (top), a description of how each scale relates to the relevant component of language (middle, boxed text), and the putative mechanistic link between components (bottom text). Components are named representation (R), operation (O), structure (S), encoding (E). The colored boxes in the Encoding component (hierarchical memory, lexical memory) correspond to the colors of the level of linguistic representation they are associated with (i.e., S for hierarchical memory, O for lexical memory).

posterior temporal cortex (Wilson et al., 2018), but clear-cut localizationist distinctions between lexicality/structure seem unmotivated (Murphy et al., 2022d), in particular given that all lexical items intrinsically host syntactic/categorial information, such that any modification to lexico-semantic content in a given experimental paradigm will also be expected to tax syntactic processing (Matchin, 2023).

While much of the evidence surveyed here will naturally come from studies of language, my goal is to make reasonable inferences about what the neurocomputational architecture for syntax must be, by drawing on what we already know about domain-general neurobiological systems. As such, I will also consult research from the working memory literature and the binding literature.

I will now turn to motivating each component of ROSE, before presenting converging causal evidence, and concluding with a discussion of future prospects. Before doing so, I note here that the discussion below should be seen as being aligned with assumptions about language processing that try and integrate computation-level accounts with algorithm-level accounts, such as the ‘one-system’ contention (Lewis & Phillips, 2015) that grammatical theories and language processing models describe the same cognitive system. This is evidenced by grammar-parser misalignments occurring as a consequence of limitations in domain-general systems such as memory access and control mechanisms, and is also evidenced by the convergence between online and offline responses to grammatical anomalies (Sprouse & Almeida, 2013). While I do not aim here to adjudicate between rival parsing models (e.g., various flavours of minimalist parsers), I note that one cannot even begin to robustly test distinct parsing models in a neurophysiologically plausible way if the appropriate level of neural organization is not first arrived at for the specific process under consideration. The architecture of ROSE is precisely that: an architecture, compatible with a range of psycholinguistic accounts.

5. Representation

Recent work at the single-unit level in humans has elucidated place and time cells, face cells, stubby shape cells, spiky shape cells, and cells sensitive to animacy (Bao et al., 2020). What will single-unit resolution recordings for the various properties of language look like? Under ROSE, small ensembles of temporarily cooperating neurons, some of which are highly specialized for particular lexico-semantic feature types (e.g., ϕ -features (see Glossary), [+Q] (Question) features, categorial (n , v) features), collectively represent atomic features that operate as feature-bundles. This aligns with standard assumptions that lexical items are simplex conceptual atoms. Semantic features of lexical items likely “combine sparse codes with the flexibility and combinatorial richness of assembly codes” (Friederici & Singer, 2015), with semantically related items exhibiting overlapping single-unit responses across medial temporal and lateral posterior middle temporal cortices, depending on approximation to canonical categories that these regions seem sensitive to. For instance, posterior middle temporal cortex may serve language-specific representational features, such as abstract word meaning, and may be involved in lexicalization of non-linguistic concepts. Verguts (2017) plausibly speculates that different neural populations which have their spiking patterns modulated by γ rhythms are, “presumably, cognitive representations”. The full spread of concept-specific activation profiles for linguistic features remains to be comprehensively mapped, in particular those pertaining to features with grammatical/formal status, but new research is beginning to emerge here. For example, the temporal features of lexical items appear to be partially subserved by time perception circuits in parietal cortex (Johari et al., 2023).

Syntactic features are assumed here to be represented much like other long-term memory representations. Recent work suggests that single cells in human medial temporal lobe can shift their concept-related selectivity based on task demands while other cells are less susceptible to being re-coded (Donoghue et al., 2023). For syntactic features, it is possible that a similar kind of mismatch of fixed vs. flexible cells exists, and that this varies across feature type (e.g., formal, semantic, categorial). To elaborate on this point further, and to stress caution when assigning concept-related or feature-related neuronal profiles, consider how grid cells had their representational profile expand from spatial navigation to auditory navigation to conceptual navigation (Mok & Love, 2019). In contrast, face cells have enjoyed the opposite journey, shifting from concept cell status to recently being implicated in navigation (Khandhadia et al., 2023). Similar journeys may soon await syntax-related and semantics-related cells.

The major, relevant activity scales for the R and O components of ROSE are as follows:

SUA (single-unit activity): Extracellularly-recorded activity of an individual neuron.

MUA (multi-unit activity): Multiple neurons, between ~ 50 and $300 \mu\text{m}$ (Buzsáki, 2004).

ESA (envelope of spiking activity): The envelope of MUA (Ahmadi et al., 2021).

LFP (local field potential): Mesoscopic, large number of neurons, from $\sim 250 \mu\text{m}$ to several millimeters (Buzsáki et al., 2012).

Before moving to the specifics of the current model, I stress that the notion of representation entertained here is synonymous with atomic feature or unit: I am not concerned with, for example, notions of representation found with formulations such as ‘the syntactic representation of multiple *wh*-movement’, or ‘the representation of long-distance pronominal binding relations’. I am concerned with elementary representations – there are also *representations of structure* or *workspace representations*, but to avoid terminological confusion I will simply refer to these below as S and E.

5.1. Basic units

The atoms of linguistic computation are commonly assumed to be bundles of features or functional categories (Chomsky, 1967, 1974; Ramchand & Svenonius, 2014). However, linguists within, for example, the Distributed Morphology tradition have abandoned hope in a coherent notion of ‘word’; there are simply groups of features coding for conceptual roots, derivations and inflections (Gwilliams, 2020). Morphology and syntax are part of the same structure-building system, hence why we can generate words that,

structurally, look like ‘mini sentences’, like *anti-institutionalization*. In polysynthetic languages, a single word can be composed of many productive morphemes, representing complex meanings. Although further specifics will not concern us, ROSE can accommodate (i) sets of syntactic atoms (R), (ii) mapping rules between syntax and concepts (O), and (iii) mapping rules between syntax and form (i.e., production) (Preminger, 2021). ROSE therefore permits the single-unit or assembly-based representations of distinct features from these domains.

Stored linguistic knowledge can involve the mapping from a semantic feature, to a syntactic feature, and to a phonological feature, and this process is hypothesized to take place at the O level (see below). Returning again to model testability, I am predicting here that single-unit recordings will *not* be able to detect effects of accessing a single linguistic feature and then utilizing it in multiple (underspecified) ways across linguistic sub-systems (e.g., syntax-form mappings).

Emerging evidence for this framework comes from Dijksterhuis et al. (2022), in which pronouns referring to previous discourse entities reactivate single cells in the human medial temporal lobe. Other work points to single-neuron representations of ambiguous words (specifically, homonym), also in the medial temporal lobe (Samimizad et al., 2022). Relatedly, Cai et al. (2022) conducted single-neuron recordings in five patients undergoing planned intraoperative interventions, and exposed them to auditory sentence recordings. They found that many neurons in lateral inferior frontal cortex and lateral middle temporal cortex responded significantly to a variety of lexical features during comprehension (lexico-semantic features and thematic roles), and some were also engaged in accurate next-word prediction.

These recent studies all point to the existence of coordinated assemblies of neurons that encode a variety of lexico-semantic features. This is likely done in a mostly redundant format, although the range of inter-featural combinations available to a given representation (e.g., syntactic feature X can combine with sets Y and Z, but feature P can only combine with set Y) may relate to whether an atomic feature is sparsely (cell-specific) or redundantly encoded.

Other work from Nelson et al. (2022) discovered preferential activity for content words over function words in the anterior temporal lobe, independent of word length and word position in the sentence. Indeed, anterior temporal regions appear to be involved in conceptual combination in basic phrases, but not syntactic combination (Pyllkkänen, 2019), important for semantic hub-based operations (Kocsis et al., 2023). More generally, concept cells that preferentially activate for stimuli that occupy a certain position in some categorial axis (e.g., animate/inanimate, spiky/stubby; Bao et al., 2020), seem to support declarative memory formation. Together with the more established finding that high frequency ripple oscillations (~150–250 Hz) and fast ripple (250–500 Hz) activity are both modulated by human memory encoding and recall across the cortex (Kucewicz et al., 2014), these new results point to the involvement of local cortical circuits and individual neurons encoding basic atomic features.

Lastly, an extensive study of lexical access in epilepsy patients (via common object naming) has revealed another strong candidate for a lexico-semantic feature hub, the mid-fusiform gyrus and surrounding ventro-temporal cortex, which are strongly associated with post-operative naming decline (Snyder et al., 2023). Importantly, Snyder and colleagues note that these loci coincide with the sites of susceptibility artifacts during echo-planar imaging, potentially explaining why this region has been previously underappreciated with respect to its role in lexical access.

Altogether, these recent results indicate the existence of previously under-appreciated scales of neural complexity and cortical sites that code for basic R units. With respect to order of magnitude estimations, it seems empirically justified from recent literature to hypothesize that distinct syntactic and semantic features can be encoded at the cellular level. No other present neurolinguistic models entertain this assumption (see ‘Current Neural Models of Syntax’ above), and it forms the basis of ROSE.

5.2. Mapping from R to O

How can we relate these ideas to O, the component of ROSE responsible for manipulating and combining R units rather than simply accessing them? I will suggest in the following sections that the relations between multi-unit activity and population signals hold the answer.

Local field potentials (LFPs) reflect the common synaptic activity of a population of neighboring neurons (or the weighted sum of the aggregate activity of a group of neurons, reflecting mostly postsynaptic activity) (Buzsáki et al., 2012; Freeman, 1975; Jansen et al., 2015; McCarty et al., 2022; Łeński et al., 2013). Spikes are short-timed high-frequency content signals reflecting individual cellular activity. Neural synchronization can be evinced by temporally relating spiking activity to the background oscillations of LFPs (Fries, 2009, 2015), and this relationship has been documented across multiple brain regions and cognitive functions (Zarei et al., 2020). This spike-phase coupling has functional consequences, such that in rats the coupling between spike timing and the LFP phase in β oscillations represents sensory information, with an inverted bell-shaped tuning curve (Zarei et al., 2020).

LFPs are a highly effective means of exposing what state a given cortical region is in, since they capture general dynamics not specific to any individual cell, but also some cells that do not spike. In the same way that there is likely much information available at the LFP level that is not represented at the single-unit level (Kay & Lazzara, 2010) – dynamics and emergent properties exist that can only be detected at the level of summed activity over millions of neurons – so too is it expected to be the case that there are aspects of cortical computation that are only represented at the interactional, global scale, and not at the LFP or spike level. This is a basic presupposition of ROSE, but also many other frameworks in cognitive neuroscience (e.g., Pessoa, 2023). An exemplar candidate process here is working memory, which seems to involve discontinuous bouts of spiking activity, as opposed to steady-state neural dynamics, with cortical rhythms being thought by some to control these dynamics, implementing executive control and allowing us to direct our memory and attentional resources at will (Buschman & Miller, 2023).

Relating R to O is far from trivial. Consider how communication-through-coherence has typically been assumed to reflect phase-synchronization between oscillators. Recent work has offered an alternative mechanism, through which coherence is the consequence

of communication and emerges because spiking activity in a sending area causes post-synaptic potentials in the same but also other areas (Schneider et al., 2021). These authors identified afferent synaptic inputs rather than spiking entrainment as the principal determinant of coherence, opening up new directions for framing the relation between units and coherence. LFP coherence appears to be determined by two factors (Schneider et al., 2021): (i) coherence due to the direct contribution of afferent synaptic inputs; (ii) coherence between the sender LFP and the summed population spiking activity in the receiver. Coherence therefore depends on connectivity strength and oscillation power, and does not need purely oscillatory coupling or spike-phase locking in a receiver.

Further complexities arise here. Perhaps the biggest obstacle concerns the observation that cognitive processes do not necessarily lead to an increase in oscillatory power, and there is no necessary or clear connection between neural activity and computational complexity. For example, rhythms may emerge under stationary conditions and for low-dimensional sensory inputs. Schneider et al. (2021) found in monkeys that β coherence and power were most prominent during fixation, not during memory and movement. In macaque V1, high γ oscillations have been found for low-dimensional visual stimuli highly redundant across space, but these oscillations disappear for more salient stimuli (Uran et al., 2021). Genuine inter-areal phase-synchronization has been extensively documented, particularly in hippocampal θ , but the point to be made here is that although the basics of ROSE are well-supported, the specific mechanistic, causal interactions between levels remains very much an open question.

Nevertheless, successfully relating the two fundamental signals discussed in this section (spike-LFP) can provide us with a comprehensive explanation regarding the neurobiology of cognition (Perge et al., 2014). Since many signals picked up by the LFP will also very likely be able to be found at the unit level, care must be taken to map out assembly-level effects from single-unit responses and also from multiple, clustered single-unit responses, to establish which levels of linguistic resolution can confidently be mapped to units.

At this point, it is important to stress a clear, falsifiable element of ROSE. I am hypothesizing that representation-specific information bits will be detected in future single-unit research, but that this type of electrophysiological research will *not* detect supra-lexical, structural information (e.g., the S in ROSE). I am also predicting domain-specific effects in spike-LFP coupling for lexicality.

5.3. Gain-field mechanisms

I have so far presented a framework for representing and accessing basic features. However, there also exists a plausible neural code for representing multiple features at once, as in the case of feature-bundles that compose into objects manipulable and searchable by syntax, in the form of a gain-field mechanism (Botvinick & Watanabe, 2007). Gain-field mechanisms can conjoin information coded at the spike level across distinct domains, and in the case of lexical features, we might expect portions of posterior middle temporal cortex (serving as an interface between conceptual representations in anterior temporal cortex, and thematic representations in angular gyrus; Matchin and Hickok, 2020) to be tuned to the product of two variables (conceptual, event, etc.), and would hence exhibit a preference for a specific conceptual and thematic space (see Martin, 2020 for a comprehensive proposal in this spirit). For instance, research utilizing fMRI suggests that the superior temporal sulcus is subdivided into regions that encode agents, verbs, and patients, independent of temporal order (Frankland & Greene, 2015). Pushing these ideas further, posterior middle temporal gyrus and inferior parietal lobe both respond to conceptual information from three separate input modalities (action, motion, sound), whereas other cortical areas respond in a bimodal or unimodal manner (Kuhnke et al., 2022), suggesting that single-unit responses in these two regions will likely code for conceptual features called upon by complex lexical instructions triggered by sensorimotor γ .

The posterior temporal sulcus is well-placed to organize much of this activity. It is closely connected to areas responsible for lexical search (posterior middle temporal gyrus), conceptual combination (anterior temporal lobe) and verbal/event semantics (angular gyrus). This argument is made with great force in Matchin and Hickok (2020). Compare this with the organization of inferior frontal cortex: sub-portions recruited for semantic control are “topographically sandwiched” (Chiou et al., 2022) between the multiple-demand and default-mode systems, and intracranial recordings can also evince distinct topographies for frontal control regions in high γ activity (Assem et al., 2023). This mosaic-like architecture of frontotemporal language network nodes (Murphy et al., 2023) can likely inform the architecture of ROSE, such that cortical sites of clear functional tessellation are predicted to be the very same sites of close interactivity between the ROSE components. One potential hypothesis to entertain here is that the portions of pSTS that show effects in high γ to basic syntactic operations will be flanked by temporo-parietal regions that engage for sentence-level composition effects in some domain of low-frequency power shifts.

What other neurobiological details are relevant here? It is known that neurons can participate in multiple large networks, simultaneously, via firing at different frequencies (Bucher et al., 2006), contributing to all components of ROSE. Neurons in medial temporal and medial parietal cortices (Woolnough et al., 2020) would be readily capable of coding the product of multiple variables along category-sensitive cortices, given the categorial topology of these regions (see Murphy, 2020c for limitations of gain modulation models for higher-order aspects of language, beyond the lexical level). Single-unit recordings and cortical stimulation mapping in humans suggest that the medial temporal lobe codes for aspects of subjective memory and conceptual recall (Fried, 2022). A common set of mechanisms for gain modulation have also been identified: GABAergic inhibition, synaptically driven fluctuations in membrane potential, and changes in cellular conductance (Ferguson & Cardin, 2020).

Although ROSE simply requires features of language-relevant representations to be coded at the spike and ensemble level, indexed by gain-field mechanisms, other recent insights into single-cell computation are emerging that might refine this framework (Gallistel, 2021; Poeppel & Idsardi, 2022). Although synaptic weight remains the focus of information models, neurons are eukaryotic cells with multiple information storage and processing mechanisms (Fitch, 2021), including aspects of wetware (gene transcription, protein phosphorylation; see Cohen, 2002) and cell morphology (dendritic form), and features of non-synaptic information-processing may contribute to the development of the R component of ROSE, in addition to R-to-O mappings. For instance, computation via wetware is substantially less expensive than cell signalling (Sterling & Laughlin, 2015). The single cell is ultimately where genetics,

thermodynamics and theories of computation can meet (Niven, 2016). Neuronal excitability itself is an intracellular process interacting with synaptic plasticity, capable of being transferred via mRNA transplants across cells (Abraham et al., 2019; Lisman et al., 2018). If one is also concerned with issues of computational efficiency in syntax (Murphy et al., 2022a), intracellular computations (pertaining to synaptic weights, electrochemical dynamics and cell morphology) appear to operate near the noisy coding optimum (Rieke et al., 1997) and are also orders of magnitude less costly than intercellular signalling (Gallistel, 2017). For a generative model of synaptic and intracellular dynamics for memory formations that follows this spirit, see Gershman (2023) (see also Gaito, 1976). One possibility for ROSE, if we assume that linguistic features are represented in an intracellular molecular format, is that intracellular computations pertain to atomic representations and variables (generative models), while synaptic plasticity is responsible for updating pertinent parameters of inference models (a parametrized mapping from observations to a distribution over latent causes) (Gershman, 2023), contributing to free-energy minimization.

A genuine explanation for basic properties of linguistic information access may be in the near future achievable via this reverse-engineering perspective of basic properties of cellular computation, in particular if we follow Prasada (2021) in assuming that Gallistel's (2021) observations about the single-cell basis of memory must also be applied equally to conceptual representations relevant to higher-order cognition. For instance, memories for abstract quantitative facts, concerning durations, distances, numerosities, rates and probabilities, are claimed by Gallistel (2021) to be stored in terms of representations that depend on information-bearing molecules within neurons. Basic human concepts manipulated by language also bear abstract and quantitative dimensions (e.g., concrete concepts and their individuation criteria via numeric quantification; Gotham, 2016) that exhibit considerable internal complexity (Chomsky, 2000), potentially rendering them compatible with this scale of neural representation.

As Trettenbrein (2016) summarizes the relevant literature: “[M]emory persists despite synapses having been destroyed and synapses are turning over at very high rates even when nothing is being learned”. Pursuing this intuition, Ryan et al. (2015) suggest that synapses should be understood as providing “access points” to information already stored within cells. Linked memories furthermore appear to share synaptic clusters within the dendrites of overlapping neural populations, and the locus of protein synthesis shapes the structure of the memory trace (Kastellakis et al., 2016).

How can we begin to relate these issues of basic information processing to other scales of complexity? Many researchers in systems neuroscience are embracing Chuderski's (2016, p. 1) assessment that “[c]ross-frequency coupling may serve as the optimal level of description of neurocognitive processes, integrating their genetic, structural, neurochemical, and bioelectrical underlying factors with explanations in terms of cognitive operations driven by neuronal oscillations”. It is in this spirit that ROSE aims to mechanistically link both single-unit and population-level dynamics for natural language syntax. This is the theme we will turn to below.

5.4. Cells to circuits

One final source of tension here, though certainly not unresolvable, is between Sherringtonian and Hopfieldian views of neural computation. This is essentially a distinction between anchoring computation around biophysical details and highly specified cellular connections (focusing on the transformation of signals by nodes in a point-to-point architecture, viewing cognition as the result of patterns of node-to-node connections whereby nodes transform representations), and viewing it as instead arising from dynamics of neural spaces and populations (focusing on representational spaces with computation considered to be the transformation between spaces; an extreme interpretation of the Hopfieldian view omits biophysical details altogether) (Barack & Krakauer, 2021). At the heart of ROSE (in particular, the transition from R to O) lies the question of which domains of language specifically demand attention from either of these views (the neuron doctrine vs. the population doctrine), and to what extent they can be unified. These concerns lead us into one of the most difficult challenges for modern cognitive neuroscience: varying across domains, brain areas, behaviors, and species, do single-unit responses possess explanatory power because they are part of a larger population, or, conversely, do population dynamics possess explanatory power because of the inherent computations performed by single-unit constituents? For example, evolutionarily older brain areas may be explained better via Sherringtonian accounts, but more recently evolved structured might not.

Quite independently of these challenges, the aspects of R reviewed here allow us to go some way from coding distinct features (unit spikes) to feature-bundles (unit spikes coordinated by LFPs). Our next topic concerns operations over these objects.

6. Operation

The ROSE model makes direct predictions for what type of experimental paradigms will be optimally utilized across distinct recording scales. After all, models are only useful insofar as they can be falsified and have their predicted effects quantified. This becomes highly salient with the case of basic linguistic operations (O).

The current model will assume that high γ activity indexes operations pertaining to transformations of R. γ oscillations can be generated via the reciprocal interaction between excitatory glutamatergic and inhibitory GABAergic neurons (Welle & Contreras, 2017), although their comprehensive neurochemical profile remains unsettled. High γ is assumed to index local cortical activity (multi-unit activity) (Leszczyński et al., 2020). Adopting assumptions in Murphy (2020a), narrowband and broadband γ parcellate representations of distinct complexity during coupling with low frequencies such as α and θ , such that broadband γ transforms complex linguistic features and narrowband γ extracts more elementary representations (for empirical support of this complexity contrast outside of language, see Saleem et al., 2017; Storchi et al., 2017). In this section, I will focus more on the basic properties of high γ activity, and will return to these concerns of low frequency interactivity for the S and E components.

6.1. The meaning of γ

A fundamental assumption of ROSE is that much (perhaps all) of the relevant space of computation at the O level takes place within the varying dimensions of γ . It is therefore necessary here to consider the different types of γ rhythms in cognition, rather than viewing γ as a monolithic unit. The integration between broadband and slow (30–50Hz) γ is an interesting case in this respect. Broadband γ correlates with neuronal spiking; spiking is phase-locked to slow γ ; and, in turn, fast γ exhibits coupling with slow γ (Bahramisharif et al., 2016). Intracranial recordings suggest that, in contrast to fast γ , slow γ does not seem to be triggered in a strictly item-specific manner, and so slow γ power likely does not carry information via amplitude but is rather responsible for temporally organizing other signals (Bahramasharif et al., 2018); see also Bartoli et al. (2019). It is possible that the sites of slow γ rhythms act as relay stations between the sites of slow rhythms and the ultimate representational content accessed via broadband γ clusters (triggering the R level), necessitated and structured by specific projections. Indeed, this may demand an expansion of the δ - θ - γ code (see below) in Murphy (2020a) to a δ - θ - γ^L - γ^H code (L = low, H = high).

Recent experimental work helps inform our understanding of the processes indexed by γ . Woolnough et al. (2021) show that broadband high γ indexes orthographic-to-lexical transformations. Other work documents γ signatures of basic lexical conversions during reading aloud single words (exception, regular, pseudowords) (Woolnough, Donos, et al., 2022): mid-fusiform and inferior frontal cortex encodes lexicality; word frequency is encoded by mid-fusiform (earliest sensitivity), inferior frontal and inferior parietal cortices; and orthographic neighborhood sensitivity is found in inferior parietal sulcus. This points to a distributed network for distinct features that compose into lexical items. Or, more specifically, it suggests that these regions are involved in regulating spiking activity across multiple sites encoding these features, potentially via spike-phase coupling or a similar mechanism. Different cortical sites engage for various types of sensorimotor transformations, e.g., posterior parietal cortex for orthographic-to-lexical or tactile transformations in braille (Liu, Gao, et al., 2023). Other portions of cortex are likely dedicated to varying degrees to aspects of R that are accessed via O. For example, living and non-living nouns can be selectively impaired (Bi et al., 2016) and neurally represented (Chan et al., 2011), whilst nouns and verbs are also selectively impaired (Daniele et al., 1994) and neurally represented (Yang et al., 2017). The possibility that these dissociations are also driven by the lexico-semantic features of nouns and verbs (Alyahya et al., 2018), rather than syntactic category, further highlights the importance of representational resolution.

High γ is also a strong candidate for indexing the mapping of other basic psycholinguistic features, such as mappings between ortho-phonological information and meaning (de Zubicaray et al., 2022). Angular gyrus is a likely hub for γ -encoded O transformations for higher-order verbal semantic R units, being implicated in thematic/event structure (Graves et al., 2022) and the reconstruction of semantics from word-level phonology (Junker et al., 2023). Low frequency MEG activity in anterior temporal lobe and ventromedial prefrontal cortex seems to be sensitive to properties of conceptual combination (e.g., conceptual specificity), rather than syntactic structure itself (Pylkkänen, 2019), and future research could explore how these regions coordinate the activity of faster, cross-cortical activity likely recruited for accessing the relevant R features.

Consider next the results in Artoni et al. (2020). These authors constructed homophonous phrases with the same acoustic content, but which can be interpreted as either noun phrases or verb phrases depending of their syntactic context. Using intracranial recordings, they showed that VPs – semantically more complex than NPs – elicited greater activity in the high γ (150–300Hz) range than NPs across language-relevant areas. Again, we see clear involvement of high frequency activity in representational transformations (converting identical sensory information into semantically distinct data structures, with local cortical activity increases indexed by high frequency power modulations).

Other recent intracranial work directly supports this hypothesis concerning high γ indexing of lower to higher-order feature transformations. Focusing on auditory cortex and surrounding sites of superior temporal gyrus, Keshishian et al. (2023) showed a transition from the representation of early acoustic, phonetic and phonotactic features in high γ , to the later representation of lexico-semantic features, with these higher-order semantic features being represented further away from primary auditory cortex. The representation of earlier features was sustained throughout, with the transformation of speech sounds to lexical meaning being indexed by high γ .

Overall, these studies suggest that high γ is involved in the *conversion* or *mapping* of primitive units to larger feature-bundles that compose into complex linguistic objects. This forms a major aspect of ROSE, and is directly testable and falsifiable. These linguistic representations often seem to be used by the same cortical sites in both comprehension and production (Hu et al., 2022). The cortex appears to implement a range of reusable computations (Marcus et al., 2014), permitting this generic mapping process to take scope over (evolutionarily) novel feature spaces. For example, prefrontal cortex may host circuits supporting variable binding, sequencing, gating and working memory storage (syntax-external demands), while lateral posterior temporal cortex might more reliably and efficiently subserve cross-modal semantic integration, supraordinate categorization and recursive hierarchical processing (syntax-internal demands).

This theme of conversion and mapping is directly related to concerns of the type/token distinction. Other neural models of language have addressed the type/token issue comprehensively (Baggio, 2018), providing a level of depth that I will not attempt to match presently. I will simply note that, at least in terms of the semantic network for orthographic language comprehension, a model for types, tokens and referents has recently been proposed from a large cohort of intracranial recordings (Murphy et al., 2023). This network implicates posterior superior temporal sulcus (pSTS), orbitofrontal cortex and inferior frontal sulcus as coding for types in high γ activity, with processes pertaining to lexical search and semantic coherence implicating a considerably widespread cortical network. With respect to ROSE, it is notable that pSTS and closely neighboring portions of posterior temporal cortex code for *all* three components of meaning (type, token, referent). In many ways, the present assumptions about pSTS hosting types (i.e., types at the R level via sparse coding of single-cell features, or more redundant features further away from pSTS) and its interactions with frontal and

parietal cortices generating tokens and referents provides support for core aspects of the MUC model (Baggio & Hagoort, 2011; Hagoort, 2013), but with the additional neurocomputational architecture scaling from single cell to ensemble to a coordinated, multiplexed network.

Hence, under ROSE the function of oscillations is to express a maintained representation in differential spike timings, and to coordinate the binding of distinct sets of features into what linguists describe – using progressively baroque terminology as time goes by – as a labeled set (Chomsky in the 1990s), a compositional structure (Pietroski in the 2000s), an intentional composite function (Hoshi in the 2010s), or a hylomorphic pluralistic mereological object (Adger in 2023). Many of the physiological roles that oscillations appear to play are also relevant here. As Xiong and Garfinkel (2023) summarize in a major review, oscillations can be seen as “enabling systems to avoid desensitization, to avoid chronically high and therefore toxic levels of chemicals, and to become more resistant to noise”.

7. Structure

Acquiring and manipulating embedded tree structures, in a recursive fashion, appears to be a defining human achievement. Even basic linguistic structures exhibit sensitivity to syntactic identity (Lasnik, 2017; Martin et al., 2020). There is, famously, “no escape from syntax” (Marantz, 1997). Sentence structure, in variable ways, guides a number of linguistic processes such as lexical recognition and semantic integration (Lowder et al., 2022; Pietroski, 2008, 2018). Discovering a feasible neural code for recursive syntactic composition would contribute to an explanation for the generativity of human intelligence and, potentially, the acquisition of composable functions more broadly (Dekker et al., 2022).

Thus far, I have mapped out candidate neural mechanisms for elementary linguistic representations and their manipulation. This section will begin by outlining the profile of supraordinate structures aimed to be captured by ROSE, before progressing to how this model converges with existing research.

7.1. Basic structures

The syntactic component of language involves the construction of binary-branching hierarchically organized sets via the operation MERGE. This operation initiates with lexical access, manipulating objects from the lexicon or objects part of the syntactic workspace. Given the set $\{X, Y\}$, we can either select a new lexical object and MERGE it, to form $\{Z, \{X, Y\}\}$, or we can select an existing object to form $\{X, \{X, Y\}\}$ or $\{Y, \{X, Y\}\}$. These sets are then labeled and given a syntactic identity, based on which element is most structurally prominent and easiest to search for (i.e., Z in the structure $\{Z, \{X, Y\}\}$). MERGE can also derive some set-theoretic properties of linguistic relations, such as *membership* and *term-of*, as well as the derived relation of *c-command* (sister of). In an attempt to render theoretical models more psycholinguistically compatible, MERGE has recently been defined as an operation on a workspace and its objects (Chomsky et al., 2019, 2023; Marcolli et al., 2023), formalized as follows (WS = workspace; P/Q = workspace objects; X = additional elements):

$$WS = \{P, Q, \dots\}$$

$$\text{MERGE}(P, Q, WS) = WS' = \{\{P, Q\}, X_1, \dots, X_n\}$$

A basic case of traditional External MERGE (responsible for argument structure) can be represented as:

$$WS = [X, Y, Z] \rightarrow \text{MERGE}(X, Y) \rightarrow WS' = [\{X, Y\}, Z]$$

In contrast, we can also implement Internal MERGE (‘movement’; responsible for discourse- and information-related properties):

$$WS = [\{X, Y\}, Z] \rightarrow \text{MERGE}(X, \{X, Y\}) \rightarrow WS' = [\{X, \{X, Y\}\}, Z]$$

The execution of MERGE relates ultimately to structural relations, rather than to independent pressures like communicative priorities (Murphy, 2020b). As Hagoort (2023) comprehensively reviews, the computational system of language seems to be related to neural signals integrating perception and action, providing humans with novel modes of planning and interpretation, whereby lexical units and unification processes like MERGE provide “an imaginary space that transcends the influence of direct perception-action cycles” (Hagoort, 2023, p. 2). This positions MERGE outside of the direct influence of sensorimotor γ signatures, for example.

I will be concerned here with exploring candidate neural mechanisms for MERGE in an effort to construct the S component of ROSE, putting aside some of the performance-related issues pertaining to real-time parsing, which require deeper empirical exploration.

7.2. Syntactic signatures

The most basic, and directly testable assumption of the S component of ROSE will be that the processing correlates of MERGE and labeling can be detected after posterior temporal δ phase-locks to θ either in neighboring temporal sites or inferior frontal sites, depending on the category of structure being composed. These low frequency interactions may take place in portions of posterior temporal cortex that are separate from, or only partially overlapping with, those portions of pSTS that are implicated in O via high γ sensitivity to basic compositional operations.

Dorsal arcuate fasciculus, connecting posterior temporal with posterior inferior frontal sites, contributes to syntactic encoding (Goucha et al., 2017), whereas more ventral portions, and also more anterior temporal regions, are recruited for conceptual-semantic

processes (Pylkkänen, 2019). The importance of posterior temporal cortex for the basic property of syntactic structure building cannot be emphasized enough (Matchin, den Ouden, et al., 2022, 2023; Matchin and Hickok, 2020). For example, the native language of polyglots is processed locally within posterior temporal cortex, with only minimal frontal involvement, and frontal cortex is recruited more for their many non-native language representations, presumably demanding more plastic, controlled representational access to variations in functional morphosyntactic structure (Malik-Moraleda et al., 2023). Lesion-symptom mapping of language impairments in individuals with brain tumors also suggests that while single-word production deficits are associated with inferior parietal cortex, deficits to phrase and sentence production are additionally associated with posterior temporal gyri (Ntemou et al., 2023).

These concerns help with localizing syntax, but what about the other focus of ROSE concerning neural signal complexity?

A range of converging evidence for the role of neural oscillations in posterior lateral temporal cortex coding for natural language structure is emerging (e.g., Matar et al., 2021). Importantly, the role of endogenous oscillations in neural computation, over and above the role of entrainment, has been recently documented (Duecker et al., 2021; van Bree et al., 2021). A role for δ in some aspects of structural inference, as in Martin (2020), will be developed here. The δ - θ frontotemporal interactions in S are assumed to influence medial temporal and frontal θ - γ coupling pertaining to representational bundling. This model is also supported by the low frequency tracking literature, which finds stronger δ signatures for sentence-tracking, and also chunk-tracking, in temporal cortex over frontal cortex (Jin et al., 2020). Recent work has demonstrated low frequency (i.e., low δ) cortical tracking of structure in sentences that seems to index the internal generation of structure, but not the specific compositional interpretation derived (Coopmans et al., 2022), emphasizing the role here of low frequencies in general structural inferences as opposed to lower-order representational details. Other work has highlighted how low-frequency responses to lexical items are changed by sentential context, potentially unveiling the dynamics of how word representations are transformed by syntactic structures and how this process is directly related to both temporal and frontal δ responses (Slaats et al., 2023).

By focusing on syntactic hierarchies, I put aside here issues of morphophonology, or morphosyntactic linearization, which seem to implicate inferior frontal cortex (Matchin and Hickok, 2020; Sahin et al., 2009), and which may also recruit aspects of the θ - γ code for linear sequencing (Heusser et al., 2016; Lizarazu et al., 2023). In addition, while I am focusing here on the initial, basic generation of syntax, it is worth mentioning that low frequency dynamics are likely to shift during later stages of complex sentence parsing, such that we might expect, for example, α - γ phase-amplitude coupling in lateral temporal cortex indexing global compositional processes beyond the basic MERGE-based structural inferences, following here the role of α in late-stage semantic unification (Lam et al., 2016).

There is an interesting sympathy here between my position and the claim in Martin (2020) that low frequency oscillations “are more likely indicative of the increasingly distributed nature of cell assemblies than any timescale-related activation of linguistic structure”. And, like Martin, my approach “contrasts strongly with purely statistical, frequentist, or associationist accounts because it embraces the symbolic nature of language” (Martin, 2020). Martin’s (2020) account goes into considerably more detail than the present article with respect to how we might theorize about the synthesis of sensory information with stored linguistic knowledge, but there are some other potential sympathies here between Martin’s interest in cue-based perceptual inference and internally driven generative models for externalizing formatted thought (e.g., compare with Murphy et al., 2022a). One potential divergence between these approaches concerns Martin’s (2020) claim that “higher frequency bursts of activity reflect the application of grammatical rules to infer a larger structure coded by a new assembly that has come online”. She cites Nelson et al. (2017) in support of this. Yet, as discussed below, Woolnough et al. (2023) show that Nelson et al.’s high frequency effects of syntactic parsing are confounded by lexical frequency, with γ activity not exhibiting robust sensitivity to syntactic structure. ROSE can more easily accommodate these and other findings from intracranial research. High frequency activity does indeed relate to “the retrieval of memory-based linguistic representations” (Martin, 2020), but the precise locus of “the application of grammatical rules” seems to lie elsewhere. In addition, ROSE provides a large number of specific experimental predictions, whereas Martin (2020) provides the following general prediction (also predicted under ROSE): “If linguistic structure is represented as claimed in the model, then low-frequency power and phase synchronization should increase as structure accrues”.

Neighboring domains of cognitive neuroscience provide some converging insights here. In a reward-based decision-making task utilizing EEG, Riddle et al. (2022) found that reward-evaluation was marked by frontal θ phase coupled with parietal γ , whereas goal-directed behavior was positively correlated with coupling between frontal δ to motor β amplitude. The executive, supraordinate signatures of δ -driven coupling seem clear. It seems a strong candidate for implementing the above-mentioned aspect of MERGE that is independent of bottom-up sensorimotor influences.

In the language domain, Keitel et al. (2018) analysed speech tracking in source-localised MEG data and found the following structures were tracked at particular bands: phrases (0.6–1.3 Hz), words (1.8–3 Hz), syllables (2.8–4.8 Hz) and phonemes (8–12.4 Hz). The δ rhythm which tracked phrases was coupled with β power in motor areas, which likely implements top-down speech predictions. Across humans, monkeys and mice, β seems to be generated by nearly synchronous bursts of excitatory synaptic drive targeting proximal and distal dendrites of pyramidal neurons (Sherman et al., 2016). Again, this research emphasizes the supraordinate category-sensitivity of lower bands, a basic presupposition of ROSE.

Keitel et al.’s (2017) MEG study of auditory cortical δ entrainment, and its interactions with frontoparietal networks, provide further insights. During intelligible speech processing, δ entrained with three networks: δ - β coupling occurred between δ in the left anterior superior temporal gyrus and β in left-lateralised medial orbitofrontal areas, which the authors claim reflected predictive top-down modulations of auditory encoding. δ - α coupling occurred between δ in left Heschl’s gyrus and α in anterior superior temporal gyrus. Finally, δ in right posterior superior temporal gyrus coupled with predominantly right-lateralised parietal θ , which likely reflected semantic memory engagement. Auditory δ entrainment thereby seems to be influenced by left orbitofrontal β and parietal θ . These δ - θ interactions may index the mapping of acoustic-phonemic processing to more specific morphosyntactic features, which are then subject to coordination by other δ -driven mechanisms. Relatedly, using MEG Klimovich-Gray et al. (2021) showed that the joint

support of temporal and contextual predictability reduces word and phrase-level cortical tracking in δ , likely due to less parsing effort being needed in these contexts, supporting the higher-order inferential function of δ .

Nevertheless, some recent research has pointed to potential concerns with this frequency-tagging paradigm when used with natural speech, such that models invoking endogenous synchronicity may be better placed to explain the spatiotemporal dynamics of syntax (as opposed to purely chunking via exogenous entrainment). The paradigm used by Keitel and colleagues has technical issues that may prevent it from exposing phrase-specific responses: Zhang et al. (2023) show via simulations that the 1 Hz phrase-level tracking largely originates from the pauses in natural speech. The dynamics that arise through faster δ -driven and θ -driven interactions seem less susceptible to this problem.

As an interim summary, we can briefly note here that the role of lower frequencies in indexing supra-lexical, structural inferences seems by now empirically well supported.

So far, I have focused here on concrete neural mechanisms, mostly abstracted away from parsing details. Questions of timing are here purely empirical, but interactions between these layers of the ROSE processing hierarchy afford a considerable degree of rapid flexibility. Consider how hierarchical phrase composition appears to be indexed around 200–300ms after the composition-permitting item (Hale et al., 2022; Murphy et al., 2022d). Just because δ can host, for example, three cycles per second (3 Hz), this does not mean that, therefore, syntactic computation must occur over relatively long spans (~300–350ms). The δ -coordinating activity takes place mostly in the period immediately after the trough of the cycle. Furthermore, only a portion of this post-trough period will be directly responsible for phase-amplitude coupling dynamics, not the entire trough/peak cycle. As such, this will take place over much faster periods, likely within ~80–165ms chunks, or faster (keeping purely with 3 Hz as an example). These windows are compatible with MEG-derived and EEG-derived time courses for syntactic binding and semantic composition (Murphy et al., 2022d; Pylkkänen, 2019), with effects lasting around ~90–120 ms for conceptual composition, argument structure encoding, and sensitivity to long-distance dependencies.

In addition, recent work has begun to push back against the traditional ‘syntax-first’ processing model of sentence comprehension, and has shown that syntactic categories do not appear to be identified first and also do not condition lexical-semantic integration, demanding a revision to strictly serial models of phrase structure comprehension. For instance, instead of observing a LAN-P600 complex for syntactic category violations, or only a P600 effect, Fromont et al. (2020) systematically observed an N400-P600 effect. In terms of timing relevant to ROSE, this work indicates that the initial semantics-driven properties of R and O can readily integrate with each other over time windows partially overlapping with slower (and low frequency) signals integrating syntactic information.

Reinforcing the importance of the generation of supraordinate categories, in MEG decoding of speech for basic adjective-noun phrases, “the head of the phrase, the noun, engages a much more stable set of neural representations than its modifier, the adjective” (Honari-Jahromi et al., 2021), potentially due to its labeled status. We also find β oscillations in posterior temporal cortex exhibiting sensitivity to syntactic complexity (Matar et al., 2021), positioning this as a core component of identity-attribution in syntactic labeling (Murphy, 2020a), responsible for aspects of maintenance as opposed to active structure-generation (δ - θ). Other recent work has shown clear relations between periods of syntactic dependency resolution and frontotemporal α and β dynamics, seemingly facilitating inhibition and reactivation parsing processes (Zioga et al., 2023).

This section has discussed possible signature of syntax, and has suggested that a limited set of low frequency dynamics repeatedly crop up when researchers design experimental paradigms that isolate structure-marking moments of natural language parsing. This helps us construct the S in ROSE. To reiterate a major implication of ROSE, one of the testable predictions from the present model is that we will *not* find reliable signatures of syntax at lower levels of neural complexity, such as signals emerging from single-unit or even ensemble activity. Instead, structural inferences are hypothesized to be unique to population-level, global, slower dynamics (see

7.3. Mapping from O to S

One of the earliest stages of transitioning from O to S likely comes in the form of activating in parallel multiple (and potentially overlapping) unit groups coding for R but being manipulated, mapped, or transformed by γ . It has recently been discovered via human intracerebral recordings that high γ oscillations (70–200Hz) can exhibit long-range phase synchronization, which appears behaviorally relevant in a response-inhibition task (Arnulfo et al., 2020). This broadens the scope for simultaneously active (bound) linguistic features to be organized into a set via cross-cortical manipulation (coordinated, under ROSE, via low frequency activity in the service of workspace construction; see below). This approximates the formal notion of unordered binary set-formation (Chomsky et al., 2019) more so than the linear feature-clocking of phase-amplitude coupling suggested in Murphy (2020a). The joint coordination and activation of cross-cortical linguistic features (free from any serialization constrained via phase-amplitude coupling) may constitute one of the earliest stages of phrase structure building, prior to morphosyntactic linearization.

This suggests that, prior to structural identity being inferred by slower rhythms, multiple featural transformations at O could occur in parallel across distinct cortical sites via γ - γ long-range phase synchronization. This set of objects would be accessible to lower frequency phase-locking, which then ‘hosts’ these γ cycles in a manner that realizes the basic property of a set with multiple members, to be immediately subject to symmetry-breaking (labeling, headedness, etc.) operations, such as the modulation of the dominant frequency of either of the γ cycles to discriminate between them, such as the above-mentioned cases of different γ rhythms seeming to index different types of representational complexity.

This topic leads us to the question of how exactly low frequency rhythms track syntactic information in the first place.

7.4. Low frequency structure-tracking

One of the most important research directions in neurolinguistics that pertains specifically to the S component of ROSE is the low frequency tracking literature (Di Liberto et al., 2018; Ding et al., 2016; Jin et al., 2020; Keitel et al., 2018; Lu et al., 2022a; Lu et al., 2022b; Schmidt et al., 2022). The most recent advances here have shown separable low frequency responses to syntactic rule-based chunking independently of lexico-semantic features (Lu et al., 2022a, 2022b), constituting an independent neural process from basic statistical analysis of word features and distributional statistics pertaining to entropy and surprisal (Slaats & Martin, 2023). Other seminal work includes Kaufeld et al.'s (2020) demonstration of how δ -band scalp EEG activity is modulated by lexically driven combinatorial processing beyond prosody.

What makes low frequency behavior highly relevant here is that certain tracking effects may be unique to higher cognition. Multi-syllabic zebra finch songs do not result in slow neural activity matching the time scales of specific chunks, and we instead find bursts of discrete, transient activity for each syllable, rendering this appropriate for item-based state transition models, but not models invoking syntactic structure (Long et al., 2010; for further discussion, see Schlenker et al., 2022). There is also recent evidence for the role of a category-sensitive phrase-building (labeling) mechanism driving the cortical tracking (via low frequencies) of hierarchical linguistic structures (Burroughs et al., 2021), as predicted in Murphy (2020a) and in line with the present ROSE architecture.

Despite the above reservations about frequency-tagging paradigms when applied to naturalistic speech, neural envelope tracking seems vital for a number of comprehension mechanisms, and is decreased in individuals with post-stroke aphasia (De Clercq et al., 2022). Low frequency cortical activity tracks both overt and covert prosodic changes, and this tracking interplays with syntactic processing. Using scalp EEG, Glushko et al. (2022) showed that alignment of syntax and prosody boosted EEG responses, whereas their misalignment had the opposite effect. This was true for both overt and imagined prosody. A range of studies have shown how prosody serves as an aid to syntactic parsing, such that speakers tend to use stronger prosodic boundaries to mark left dependencies (Degano et al., 2022). Yet, as Glushko et al. (2022) demonstrated, some signature of syntax is still provided with δ tracking, even if constituent structure is not uniquely encoded via δ frequency-tagging.

Consider also the findings of Rimmele et al. (2022). Using MEG, these authors had participants listen to disyllabic words presented at a rate of 4 syllables per second. They found that lexical content (as opposed to syllable-transition information) activated a left-lateralised frontal and superior/middle temporal network. The authors discovered δ - θ phase-amplitude coupling in middle temporal gyrus and superior temporal gyrus in conditions with lexical, transitional and syllable information, but not with only syllable information, suggesting that syllable information is exploited for lexical-level processing. As noted above, ROSE places δ - θ interactions as part of a more general syntactic, categorization process, not unique to 'word'-level elements, applying also to sets of lexical objects to form phrases. Purely at the level of speech properties, there appears to be a role for θ tracking throughout sustained acoustic fluctuations, but a greater involvement of δ tracking at speech onset (Chalas et al., 2023).

Other supporting evidence for ROSE comes from Gross et al. (2013), who discovered δ - θ phase-phase coupling during speech perception, with θ also modulating the amplitude of γ , suggesting that δ phase likely modulates θ in distinct ways depending on the computation. Halgren et al. (2017) also revealed that in the human brain cortical δ phase "robustly modulates theta power, with an increase in theta-band power during the falling phase of the ongoing delta rhythm".

It is currently an open question what type of parsing procedures are indexed by various types of δ - θ relations (e.g., phase-phase versus phase-amplitude relations). Although I am placing more emphasis on phase-amplitude coupling for ROSE, this is purely due to the cited empirical literature supporting its importance, and further research should attempt to discriminate effects at the syntax-semantics interface across different types of low frequency interactions. For our present purposes, it is sufficient to assume that *some* low frequency interactions specifically in the δ and θ ranges form the basis of inferring S.

Nevertheless, discussion of any topic at the syntax-semantics interface requires a more thoughtful dissociation between syntax and semantics. We now turn to this topic.

7.5. Dissociating structure and meaning

Contrasting with low frequency signatures of structure, high γ appears to encode elements of meaning at the minimal phrase level (Murphy et al., 2022d) and, incrementally, in orthographic sentence processing (Woolnough et al., 2023) – but not structural identity at the complex multi-phrase, syntactic node-tracking level (Woolnough et al., 2023). Importantly, Woolnough et al. (2023) failed to detect γ signatures of syntactic node structure, as initially reported in Nelson et al. (2017), likely due to Nelson et al. not including lexical frequency in their model; once this is included, structure-related parsing effects disappear in high γ . Importantly, Woolnough et al. (2023) found increased γ for Jabberwocky over Pseudoword lists, but this was crucially punctuated and not sustained across multiple words in the sentence. As such, this likely represents a signature of the basic structure-building operation, MERGE, and these Jabberwocky γ effects also lasted around 200–300ms, seemingly the right resolution for the timing of syntactic composition (Pylkkänen, 2019). When considered alongside the failure to find γ signatures for structure-building parsing models, these results conspire to suggest that operations (O) can be detected transiently via γ , and that semantic information is represented here more robustly, while structural identity itself (S) is represented more globally in low frequencies.

While these results are in line with the framing of conceptual composition in ROSE, how can we address this apparent mismatch between high γ sensitivity to phrase and sentence meaning, but not sentence structure? One thing to consider is that constructs such as the labeling algorithm from theoretical syntax may not easily map to psycholinguistic factors, and so it seems that multi-unit syntactic node opening/closure might also not be encoded in high γ . Although the signal from a basic, minimal compositional scheme might be strong enough to be detected, driven likely by its semantic properties unique to the phrasal over lexical configuration, upon

encountering more diffuse representations across multiple phrases, this may become difficult at the purely structural level. Hence, in terms of basic semantic composition operations, and perhaps also transient instances of MERGE, high γ seems sensitive. Indeed, propositional sentence-level meaning is represented in fMRI as a distributed network, not specific to any specific site (Anderson et al., 2021), already pointing to the functional utility of global mechanisms like low frequency coupling and phase synchronization.

Other converging evidence for the present model comes from Toneva et al. (2022), who show that inferred sentence meaning ('supra-lexical' meaning) can be detected via fMRI in the posterior superior temporal sulcus but *not* via MEG, suggesting again that local cortical computation via synchronized pyramidal cell firing does not code for supraordinate elements of complex syntactic structure building.

As such, structures and storage may need separate scales of encoding, which under ROSE come in the form of low frequency synchronization and cross-frequency coupling. Operations (O) can occur at the intra-lexical or extra-lexical level, depending on the type of featural manipulation being carried out: transforming graphemes to phonemes, or to conceptual representations, or triggering a cluster of R features that go beyond the simple summation of discrete features, or building incremental sentence meaning or a situation model that is independent of structural format.

Given all this, how do we dissociate syntax from semantics?

In effect, single cells under ROSE can represent formal and semantic features (similar to how they appear to represent various sound features; Leonard et al., 2022) such as root elements and categorization elements that assemble into basic syntactic objects, but structural information may be a Hopfieldian concern of population dynamics, calling upon more global (cross-cortical) and inter-areal coordination (as opposed to category-specific, unit-specific memory storage).

Quite suitably for this purpose, cross-frequency coupling has been widely linked with information integration across neuronal populations. Bybee et al. (2022) propose a role for cross-frequency coupling in the memory of discretized phase patterns, based on a principle in analog computing (subharmonic injection locking). Using a novel coupled oscillator Q-state phasor associative memory (PAM), Bybee et al. (2022) show that the presence of coupling increases the memory capacity in plastic synapses. If the present ROSE architecture is appropriate for language, then specific, memorized syntactic configurations (akin to Hagoort's syntactic schemas in posterior temporal cortex) may be stored via types of discretized phase patterns exposed by Bybee et al. (2022), readily and efficiently called upon via cross-frequency coupling. With respect to related neural mechanisms, silent synapses (Vardalaki et al., 2022) in lateral posterior temporal cortex may be called upon ('unsilenced') to store new complex syntactic schemas for rapid recall, both during learning and short-term consolidation, coordinated by the low frequency ROSE code.

Although these discussion points are less tangential to the core ROSE mechanisms, and rely on potentially quite vague and underspecified mappings between levels of linguistic complexity, this research nevertheless serves to highlight the clear potential that oscillatory phase coding has for grounding distinct sub-components of syntax.

7.6. Mapping from S to E

We have so far presented candidate neural mechanisms for R, O, and S, and have also outlined a means to map R to O, and O to S. Are there other potential means to further link R, O and S, and is there a means to further map S to E? This section will discuss vector codes and traveling oscillations as a means of positively answering these questions.

The present system of low frequency modulations of faster local cortical activity can serve to implement the algorithmic vector symbolic architecture of Eliasmith et al. (2012). Vector codes take scope over a fixed population of neurons and determine approximate values of activity across this cohort (e.g., active vs. silent). As mentioned, the existence of spike-phase coupling, seen as part of the more global system of low frequency phase coherence under ROSE, would permit a direct path from global low frequency synchrony, to a specific γ activation profile (across the trough-peak of the lower rhythm), to the vector code of this fixed population of neurons. It is known that spike-phase coupling increases with memory demand (Hanslmayr et al., 2021), but we currently lack any such evidence for syntactic composition demands, although this is predicted by ROSE. Even though this vector code itself remains obscure with respect to syntax (and requires a joint combination of single-unit recordings and LFP signatures), in principle ROSE can readily accommodate the more global dynamics that emerge from it. Indeed, ROSE leads to the prediction that syntactic node boundaries and complex, successive syntactic operations will have no robust vectorial representation at the single-unit level. For now, we can surmise that the monotonically increasing level of γ activity over the course of sentence processing (Woolnough et al., 2023) likely reflects this output of global low frequency coordination over this space of local vector codes.

One final mechanism ties together all presently discussed components of ROSE: traveling waves. Zabeh et al. (2022) show how traveling waves (in β) regulate neuronal spiking activity across space and time, being related to reward history in the monkey brain. These authors show how frontoparietal LFPs form traveling waves, and claim that wave direction is a proxy of intra-regional communication. This provides a feasible mechanism not simply for regulating δ - θ interactional dynamics in language, but also the dynamics of R units, controlling the co-activation probability of neurons in topographic networks.

Other recent work suggests that, at least in ventral temporal cortex, the propagation of event-related phase synchronization does not seem category-specific (i.e., there are few differences between faces and words) (Woolnough, Forseth, et al., 2022), suggesting that traveling waves serve a more domain-general information transfer function in this portion of cortex, while the R and O scales serve domain-specific representational and computational functions. Note here that in order for this type of research to more stringently conclude that portions of cortex are category-sensitive or selective, we would have to detect the relevant activity profiles in the *absence* of stimuli triggering a given representation, not simply when subjects are shown pictures or words depicting these representations. The propagation of phase modulation "may represent the dynamic coordination of neural processing across spatially disparate regions [...] modulating excitability of local neural populations" (Woolnough, Forseth, et al., 2022).

In contrast, in association cortex distinct types of traveling waves (feedback, top-down) that are more category-specific seem to exist (Murphy, 2020a), which may encode higher-order information. Nevertheless, Bhattacharya, Brincat, et al. (2022), in their study of monkey lateral prefrontal cortex, did not observe any changes in traveling wave profile across different working memory task sample items, which is again consistent with the view that traveling waves have a ‘meta’ network function that is independent of item identity. Essentially, S codes specifically for recursive structure generation, and traveling waves migrate these representations over to relevant workspaces in E (see below).

Much other work suggests that traveling waves can create timing relationships fostering spike-timing-dependent plasticity and memory encoding (Sreekumar et al., 2020), and that they contribute information about the recent history of activation of local networks (Muller et al., 2018). Connecting the distinct levels of ROSE, microelectrode recordings in the human brain suggest that it also seems feasible for macro-scale waves to co-occur with micro-scale waves, which can be temporally locked to single-unit spiking (Sreekumar et al., 2020). Temporal coordination between traveling waves at different spatial scales, and between waves and spiking activity, points to a role for traveling waves in neural communication. The different types of macro-vs. micro-scale traveling waves may form their own internal hierarchy of sensitivity to distinct structures or higher-order relations in language processing, e.g., global situation model maintenance vs. local phrase structure coordination.

A more ostentatious series of speculations concerns the role of brain shape in cross-cortical information transfer, such that the human brain has assumed a more globular shape than our closest relatives (Benitez-Burraco & Murphy, 2019), and this may contribute causally to explaining efficient cross-cortical synchronization, opening up new paths for traveling waves and inter-areal connectivity. Recent work in this connection has pointed to various geometric constraints on human brain function (Pang et al., 2023) and highlighted strong relations between functional connectivity profiles and critical episodes of neural regularity and complexity (Krohn et al., 2023), although presently little else can be said of direct relevance to ROSE.

For now, traveling waves seem suited to memory-related and encoding-related processing, dynamically coordinating the local storage of cortical information, forming the foundation of any notion of syntactic workspace arising out of implementations of ROSE. Bhattacharya, Brincat, et al. (2022) document rotating traveling waves relevant for working memory in prefrontal cortex in the monkey brain. These ranged from θ to β , and during task performance some waves (mostly β) increased in number in a given direction greater than during baseline conditions. Soroka and Idiart (2021) propose a model for working memories under which δ , θ and α are traveling waves, whilst simultaneously undergoing phase-amplitude coupling relations coding for the ordering of working memory items (γ) – and constraints on working memory size – by slower rhythms. In their model, the interactions between θ and γ determine the allocation of multiple items, while interference between θ and α disrupts the maintenance of the current workspace. Under ROSE, a similar architecture exists but with the additional layer of hierarchical, executive coordination by δ for syntactic inferences over workspaces.

Overall, the type of cross-frequency coupling discussed here is relevant to the S component of ROSE (e.g., δ - γ and δ - θ , but not δ - α or θ - β or β - γ), whereas the localization and spread of cross-frequency coupling via traveling waves is relevant to the E component, which we turn to next.

7.7. Summary

In brief, ROSE assumes that the amplitude of θ (involved in θ - γ bundling of elementary features for syntactic manipulation) is in turn coupled with the phase of structure-indexing δ , with δ - θ interactions alongside δ - β interactions providing an additional layer of

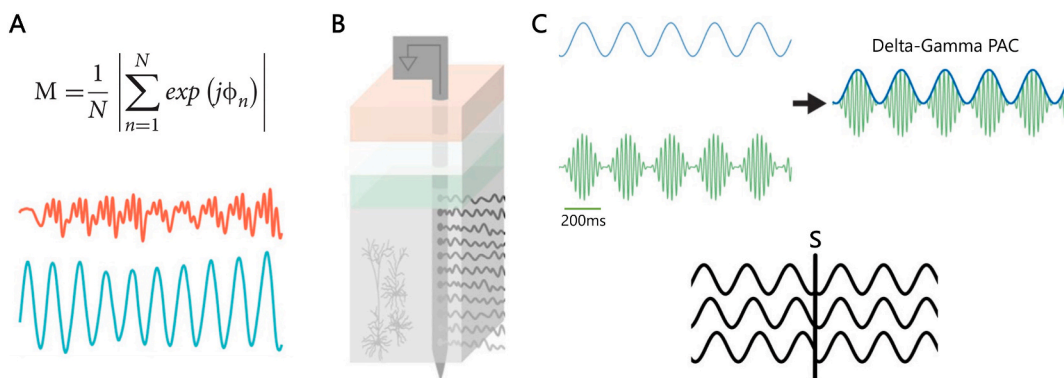


Fig. 2. Basic mechanisms of the ROSE model. (A): Spike-LFP coupling can be quantified by utilizing a phase-locking value (PLV) measure. PLV calculates the power of dependability or linking of LFP phases in spike times, by computing the angular summation between spikes to some low frequency range LFP fluctuations. Here, N shows the number of spikes, ϕ_n is related to the instantaneous phase at the time of n th spike which is determined by Hilbert transform, and $\exp(j\phi_n)$ is the complex exponential function of ϕ_n . The amplitude of vector M ($|M|$) indicates the spike-phase coupling power and its angle ($\angle M$) shows the phases of LFPs in the time of spikes occurrence. A larger value for vector M indicates that the occurrence of spikes are more likely to a specific phase of LFP, and the smaller value is related to distributed spikes across different phases. (B): A cartoon depiction of an intracranial probe detecting spike activity (adapted from Sanchez-Todo et al. (2023), Fig. A1). (C): Top: A toy example of phase-amplitude coupling (PAC). Below: A stimulus (S) results in a phase alignment of ongoing neural oscillations.

phase coding to yield recursive structure formation necessary for natural language syntax (see [Murphy, 2020a](#), for further cartographic details concerning specific frontotemporal network nodes). These are highly specific and concrete model predictions, readily testable. A depiction of the core neural mechanisms recruited by ROSE is provided ([Fig. 2](#)).

Notice that the neural codes outlined for structural inferences (S) and representational binding (R, O) are mechanistically related, but they are distinct in ways that lead to empirical predictions for the processing of logical and grammatical relations, such as negation, pronominal binding, agreement, and sentence coordination. These processes are predicted to yield high γ signatures over sites of representational binding (*à la* the binding of visual stimuli into faces or scenes; [Woolnough et al., 2020](#); see also [Yu & Lau, 2023](#)), since while they are constrained by structural factors the ultimate signature is expected to be concerned with accessing a specific representational format (R) via sensorimotor mappings (O), even if this is to be guided by the more global, supraordinate labeled identity of the current workspace (S, E). Intracranial recordings of morphosyntactic agreement, for example, could probe this issue further.

8. Encoding

Syntactic comprehension seems to require multiple workspaces. For [Chomsky \(2023, Forthcoming\)](#), there are parallel search procedures for labeling. For [Adger \(2017\)](#), one workspace is used to construct syntactic phrases, and the other is used to temporarily maintain these units once they have been transferred. This topic constitutes the final component of ROSE: encoding structures after their generation (E). Following [Murphy \(2020a\)](#), this encoding aspect can be addressed as follows: the initial θ - γ code constitutes the first workspace (sensitive to lexical memory), and the subsequent δ - θ code constitutes the second (sensitive to supraordinate, hierarchical memory). This memory architecture in fact emerges quite naturally from what we have so far claimed about R, O and S and their neural organization, but the organizational role of traveling waves plays a role that is unique to memory encoding and not, for example, the basic accessing of conceptual representations.

Traveling waves take into consideration the spatial component of neural oscillations, and how a certain phase can propagate over cortex. They have recently been implicated in predictions and temporal binding ([Alamia & VanRullen, 2023](#)), and it is this latter aspect (binding representations over time into a larger stored workspace) that is particularly relevant to ROSE. I will be concerned here with truly periodic waves with an intrinsic frequency that does not necessarily match that of sensory stimuli, i.e. those being endogenously generated by internal inferential processes. Traveling waves can create precise timing relationships that can induce spike-timing-dependent plasticity ([Bhattacharya et al., 2022b](#)); slower waves can be thought of as the ‘control’ signals that influence higher frequency spiking that carries cognitive content (hence the general division in ROSE between high frequency semantic representations and low frequency syntactic categorization). A central assumption for the E component of ROSE is that coherence between areas facilitates the transfer of phase-coded information ([Comeaux et al., 2023](#)), i.e., the transfer of grammatical rules for labeling a δ - θ complex based on the features of its high frequency γ program, aligning with how features of any given syntactic object determine the phrasal category of a structure.

To illustrate, consider the sentence ‘old men walk slowly’. During the comprehension of the first two words, the δ - γ combinatorial code coordinates the feature-bundling of the atomic data structures hosted by ‘old’ and ‘men’ ([Brennan & Martin, 2020](#)). At a minimum, this involves pSTS low frequency activity coupled with neighboring posterior temporal cortex but also cross-cortical sites responsible for the specific feature types in question (e.g., ATL, IFG) ([Murphy et al., 2022d](#)). θ - γ coupling maintains in short-term memory the relevant units (R) via high frequency activity (O) in a linear sequence ([Heusser et al., 2016](#)). At the transition between ‘men’ and ‘walk’, the supraordinate δ - θ code maintains the categorial (i.e., structural) identity of the object, in this case the negotiation between a multi-unit noun phrase and a more complex verb phrase hosting ‘old men’. During the same period, the initial lexical memory code increases its number of θ -nested chunks due to the occurrence of ‘walk’. The same transition occurs from ‘walk’ and ‘slowly’, with the exception that while the lexical memory code still increases in coupling strength, the hierarchical memory code would *decrease* closer to (but not identical to) its pre-verb baseline, due to the adjunction relation not demanding a revision of the hierarchical memory representation. The transfer of relevant lexical information (i.e., for categorization and labeling/search) would take place via interactions between these two neural codes, potentially via θ - θ phase-phase coupling or phase-locking of the θ - γ workspace and the δ - θ workspace. θ -driven dynamics effectively constitute the ‘hand-off’ of information after lexicality has been established by lower-level R and O processes, transitioning from encoding lexical memory to multi-object memory. Direct testing of these dynamics specifically with respect to syntactic workspace construction has currently not been undertaken, although much work has been carried out demonstrating increased θ - γ coupling in human hippocampus during memory formation ([Lega et al., 2012](#)), as well as enhanced frontal θ to posterior γ coupling ([Friese et al., 2013](#)), alongside the recent discovery of “a rapid neocortical theta network mechanism for flexible information encoding” ([Johnson et al., 2023](#)). Familiar operations from left-corner minimalist grammars can be appropriately parcelled onto these R, O and S levels ([Hunter, 2019](#)), but future work should treat this issue of precise parsing models with more care and tact than I have demonstrated here in this initial architectural proposal.

It is known that truly endogenous traveling waves can propagate both mesoscopically and macroscopically, within and between cortical regions, and are hence capable of indexing some of the inter-area dynamics needed by the language network. In particular, backward waves have been hypothesized to relate to top-down processes like categorial selection, while forward waves propagate from lower to higher sensory regions ([Alamia & VanRullen, 2023](#)). It therefore seems reasonable to hypothesize here that the slower δ - θ complex exhibits backward directionality (from inferior frontal regions back to posterior temporal cortex, where much of the O component takes place via γ), whereas the faster θ - γ complex exhibits mostly forward directionality (from posterior temporal towards other temporal and frontal cortices). There may be some interesting role here for α oscillations, since they have been found to propagate both forward and backward, coordinating the activity of faster rhythms in each region ([McLelland & VanRullen, 2016](#)). Further intracranial research in humans is needed here, but α may play an important role in higher order semantic integration after

successive phrase formation (i.e., after all basic ROSE components have been implemented to construct a hierarchical syntactic object) and the transfer of syntactic information across and between distinct neural networks (e.g., salience network, default-mode networks), feeding linguistic information forward to external cognitive systems but also receiving information from domain-general networks. In addition, as discussed elsewhere (Murphy et al., 2022b), thalamic structures like the pulvinar play an important role in the synchronization of oscillatory rhythms across the cortex, especially in the α band, and may play a major role in coordinating traveling waves throughout the cortex (Alamia & VanRullen, 2023). It is logical to consider this intriguing connection between α , the regulation of forward and backward traveling waves, and thalamocortical synchrony, and this topic should be investigated in future intracranial research.

Recent research is compatible with this basic model. Becker and Hervais-Adelman (2023) found that left posterior middle temporal gyrus θ -entrainment in MEG is associated with syllabic and lexical recognition during speech processing, while δ -entrainment across broader portions of posterior temporal cortex is associated with phrasal recognition. In a word and face processing task using MEG and intracranial recordings, Fellner et al. (2019) found that across a number of brain areas increases in γ power and decreases in θ power predicted memory formation irrespective of material, and that γ increases occurred significantly earlier compared to θ decreases, aligning with the general transition of γ (R/O) to θ and δ (S/E) complexes that conclude with the encoding component of ROSE. This is compatible with the Information via Desynchronization Hypothesis, which states that neural desynchronization increases the amount of information that can be neurally encoded since it allows discrete cells to transmit individual messages, as opposed to a group attempting to transmit the same message (Schneidman et al., 2011).

Related research is beginning to paint a similar picture. Lei et al. (2023) used rapid phase-encoded fMRI to map the unfolding of hemodynamic traveling waves (strongly reminiscent of neural oscillations, albeit slower). They captured neural information flows as coherent waves traveling over the cortical surface during listening, reciting, and oral cross-language interpreting. Taking 5 seconds of naturalistic reading or listening induced coherent surface waves that traveled across visual and auditory streams. During passive listening, traveling waves emerged from A1 and split into streams reaching STS and ATL in the left hemisphere. During a reading-memorizing-reciting task, traveling waves propagated through the occipital, parietal, temporal, and prefrontal cortices, before reaching speech sensorimotor and auditory cortices. This involvement of propagating waves in memory-related language tasks bolsters the current formulation of ROSE.

At the highest level of abstraction, we can summarize that δ -driven coupling constitutes the encoding of top-down syntactic information, while θ - γ coupling represents bottom-up (feature-to-assembly) level information driven more directly by perceptual inference. The remainder of this section will elaborate on this proposal and explore further connections with the above framework for R, O and S.

8.1. Syntactic memory as phase-synchronization over successive cycles

Given that we are dealing here with domain-specific cognitive properties, are there any reasons to highlight the ROSE components as being suitably distinct from a neurocomputational perspective? Consider how there appears to be a broader range of cross-frequency coupling relations in the human brain relative to the anthropoid apes, with the human cortex exhibiting a species-specific level of richness in its cross-frequency coupling profile (Maris et al., 2016), pointing to interactional dynamics as being a possible major index of human-specific computational capacities. These assumptions are bolstered by recent work showing that individual differences in syntactic processing performance is related to white matter connectivity differences between nodes of the language network (Sánchez et al., 2022). These low frequency interactional dynamics seem to be encoded via Erdős-Rényi networks (Murphy, 2020a). Future modeling of oscillatory networks for language and their connectivity profiles (Thiebaut de Schotten & Forkel, 2022) crucially need to be centred around biophysical models that are inherently compatible with recorded neural signals, rather than intuitive models of oscillations that may lead to spurious detection of rhythms (Doelling & Assaneo, 2021; van Bree et al., 2022).

This species-specific richness in cross-frequency interactions may be principally related to the expansion-fractionation-specialization (EFS) hypothesis (DiNicola & Buckner, 2021). Evolutionary expansion of human association cortex may have allowed for an archetype distributed network to fractionate into multiple specialized networks (DiNicola and Buckner place special emphasis on frontotemporal areas implicated in higher-order language). One such network seems to be anchored around a cortical mosaic for linguistic structure and meaning along the pSTS (Murphy et al., 2022d), interacting with inferior frontal cortices during more complex functional grammatical structure-building (Woolnough et al., 2023), and under ROSE would form the basis of low frequency hierarchical coupling in the δ - θ range.

At the algorithmic level, the present conception of E is compatible with the framing of syntactic working memory as arising from continuous or discrete attractor states, implemented neurally via activity in recurrent networks (Wang, 2013) and the coordination of firing patterns via low frequency phase coding.

Although my concern here has been purely architectural, with my goal being to posit strong candidate mechanisms for syntax, it goes without saying that more mathematically explicit formulations of S and E (and their interactions), alongside computational modelling of their dynamics, will be needed. Ongoing work in this space is currently addressing this topic, building off the general architectural framework presented here.

8.2. Symbolic computation

Recent directions in the neurobiology of navigation and memory are relevant to the present conception of E. As reviewed in Kurth-Nelson et al. (2023), hippocampal-cortical sequence replay and encoding is not constrained to simply repeat past experience.

Rather, this process is informed by an internal model of the world, generating representations of inferred entities not necessarily encountered physically. This active, generative capacity motivates the authors to propose that replay in the brain instantiates a form of compositional computation. A given replay sequence constitutes a set of entities strung together into a compound, whereby each entity is bound to a representation of its compound role, determining its function as part of a whole. This establishes a clear separation, with respect to composability, between entity and role (or semantics and syntax). While roles encoded by hippocampal-cortical interactions can certainly be spatial, they can also be non-spatial, and even non-spatial and non-Euclidean (Kurth-Nelson et al., 2023; Liu et al., 2019), potentially involving arbitrary roles such as ‘verb’. The entity-role bindings currently explored empirically in humans are limited to things like ‘which position’ and ‘which sequence’, but if other roles like ‘if’, ‘then’ and ‘else’ can be encoded in a similar way then replay may form a viable candidate for a neurophysiological mechanism implementing symbolic computation. This compositional nature of replay is implemented via θ - γ (and also fast ripple) hippocampal-cortical interactions (Kurth-Nelson et al., 2023), mirroring closely the present assumptions of lexical feature sequencing and basic semantic compositionality being implemented via the same dynamics and high γ activity.

8.3. Memory transfer

Other neural mechanisms are beginning to emerge for memory transfer that may bear some relevance for transferring chunks of structure to distinct cognitive systems. Interhemispheric transfer of working memories has been found to be achieved via left and right prefrontal cortex via θ synchrony, with transferred memory traces activating different ensembles than feedforward-induced traces (Brincat et al., 2021). Cortical feedforward processing has been shown to be mediated by θ and γ (Bastos et al., 2015). The assumption of ROSE is not simply that γ increases during maintenance and decreases during read-out, as in current working memory models (Lundqvist et al., 2018), but rather that this process naturally requires coordination over a set of distinct memory representations that are concurrently clustered via more global, supraordinate control mechanisms, which take the form of phase-amplitude coupling in δ - θ for syntactic category and hierarchical memory and θ - γ for ‘lexical’ (feature-bundle) memory (Fig. 1).

Intracranial recordings in humans have revealed that frontoparietal δ and θ oscillations modulate working memory representations (Johnson et al., 2018). Under the present model, these dynamics would also directly modulate syntactic working memory whilst jointly coordinating the above high frequency program for R/O.

As briefly mentioned, β increases seem to signal the build-up of syntactic predictions (Murphy, 2020a), but it also seems that β suppression in prefrontal cortex marks cortical disinhibition permitting working memories to be expressed. β suppression likely co-occurs alongside the encoding steps in ROSE (Fig. 1), in keeping with current models, while β increases at different periods of sentence processing seem to index prediction (Murphy et al., 2022d), potentially in neighboring inferior frontal sites. The transfer of working memories from one portion of cortex to another occurs at around 120ms (Brincat et al., 2021), such that working memory representations decrease after the initial increase at the receiver, signalling a ‘soft handoff’ of information whereby some trace still remains at the initial construction site during this brief period. It may be that the duration of this handoff period for natural language (as opposed to the working memory tasks in the monkey brain probed in Brincat et al., 2021) increases with the complexity of the multiplexed, compressed signal of feature-bundles to be spell-out. Indeed, it is thought that interhemispheric communication is disrupted in certain dyslexias (Dhar et al., 2010). In addition, familial sinistrality has been found to impact the brain’s responses to morphosyntactic violations (Leckey et al., 2023); the field currently lacks a consensus on the interhemispheric organization of syntax-specific and extra-syntactic comprehension mechanisms, and inter-areal analyses centred on oscillatory dynamics may well contribute here.

The recently proposed principle of *spatial computing* can be seen as another potential means of implementing aspects of E (Lundqvist et al., 2023). Spatial computing assumes that working memory item representations (indexed by β - γ interactions) are consistently moved across spatial dimensions of the cortical network, depending on task demands. Moving the representation is used to assign or change the status of an item (e.g., its temporal order, or priority). Leaving aside many other sympathies with this framework (see Lundqvist et al., 2023), the most immediate compatibility comes with the assumption that moving an item across cortex has an essential role in encoding it in part of cognitive space, rendering it accessible to other neural systems.

8.4. Alpha/beta dynamics

So far we have focused mostly on δ - θ signatures, but as indicated briefly above, other low frequency signatures seem to play essential roles in the regulation of form-meaning mappings and the integration of information from syntax-semantics into domain-general systems.

Keeping for the moment with syntactic memory, results reported in Gehrig et al. (2019) support a role for β in syntactic identity. These authors investigated speech memory representations using intracranial recordings in the left perisylvian cortex during delayed sentence reproduction in patients undergoing awake tumor surgery. Based on the memory performance of patients, they found that the phase of frontotemporal β represents sentence identity in working memory. The notion of sentential identity presupposes a labeled structure (i.e., CP, VP), seemingly represented (at least partially) by frontotemporal β . Converging with other literature, β may represent aspects of the global cognitive set going beyond syntax-specific information to include conceptual and statistical information pertaining to sentence identity that is immediately captured by structure-building, whereas the δ - θ - γ interactions discussed above code for more specific language-internal compositional processes.

Intracranial recordings of auditory language comprehension implicate frontal α / β power (8–30 Hz) in phrasal prediction/anticipation (Murphy et al., 2022d). Pefkou et al. (2017) found that both θ and γ are sensitive to syllable rate, but only β power is modulated

by comprehension rates and is insensitive to syllabic structure. This suggests, again, that θ power plays a more bottom-up role in feature-set construction (Fig. 1) while β appears to be involved in the tracking or prediction of semantic or phrasal identity.

Over the past decade, there has been a debate about whether β power effects during sentence comprehension reflect syntactic computations, or instead reflect maintenance or cognitive set updating. To briefly summarize the latest results, it appears that the latter maintenance hypothesis is most well-supported (Lewis et al., 2023). I will therefore put further discussion of this interesting issue to one side, given that these results indicate a less central importance for ROSE with respect to β power dynamics (but see Murphy, 2020a for extensive discussion, and also Rassi et al., 2023 for further evidence of the role of β in stimuli maintenance).

In parietal cortex, α enhancement seems to index syntactic working memory demands (Meyer et al., 2013). Much like the regulation of γ by α in control and attention mechanisms (Bonnefond & Jensen, 2015; Jensen et al., 2014), parietal cortex may play an important role in memory and complexity, such that low frequency rhythms originating in lateral or medial parietal cortex regulate the activity of γ -encoded O in lateral temporal cortex, and single-unit or assembly-encoded R in medial temporal or inferior frontal cortex.

Another likely site of syntactic working memory for E is inferior frontal sulcus, since this is implicated in task-related evaluation of phrasal meaning, and exhibits functional coupling with posterior temporal sites during structure composition (Murphy et al., 2022d), and is engaged for a number of semantic integration demands (Murphy et al., 2023). As such, it is expected that lower frequency components in inferior frontal sulcus and inferior parietal cortex are functionally coupled with other low frequency components coding for S, discussed above, providing the read-out of structure into short-term encoding (Makuuchi & Friederici, 2013).

Turning lastly to the issue of memory training, using MEG Wang et al. (2021) trained native German speakers in syntactically complex German sentences via comprehension tests over a series of four days. They found that successful training strengthened the use of the dorsal processing stream, with working memory-related regions in inferior frontal sulcus demonstrating decreased γ (55–95 Hz) over the course of the four days. Future work testing ROSE could explore the electrophysiological dynamics of this region, likely a source of the δ - θ coupling-driven hierarchical workspace.

All of these assumptions take place within the context of the present traveling wave framework, with lower frequencies migrating objects across the cortex, which is particularly relevant to issues of maintenance and storage. Traditional ‘standing’ waves lead to periods when all neurons in a network are turned ‘off’, whereas traveling waves can ensure that sub-portions of a network remain consistently active (Bhattacharya, Brincat, et al., 2022), directly compatible with the mosaic-like architecture of posterior temporal and inferior frontal cortices in semantic integration processes (Murphy et al., 2023). Where exactly the waves travel to during phrase composition is purely an empirical question, but some candidate regions have been suggested above. Fig. 3 summarizes some of the electrophysiological processes recruited throughout each of the components of ROSE.

8.5. Cortical spirals

The present traveling wave architecture within the world of electrophysiology should also be investigated alongside a focus in fMRI research on spiral-like, rotational wave patterns (brain spirals) that have been found to be widespread during wakefulness and rest.

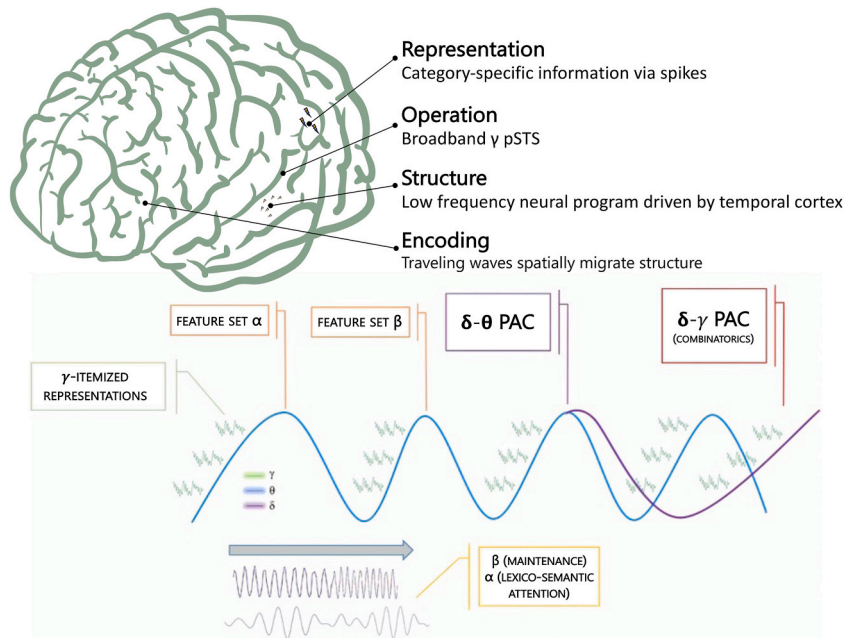


Fig. 3. Basic processes of the ROSE model. Top: A general outline of how ROSE is hypothesized to be implemented across the frontotemporal language network (see main text for specific neuroanatomical details). Bottom: A representations of the various frequency interactions proposed to implement hierarchical phrase structure building.

Brain spirals propagate across the cortex while rotating around their phase singularity centres. The rotational directions and locations of spirals appear to be task-relevant and can classify different cognitive functions (Xu et al., 2023). Brain spirals seem to organize complex spatiotemporal dynamics, and investigating the computational properties of planar propagating traveling waves, rotating traveling waves, and cortical spirals across recording modalities may prove useful in elaborating properties of global brain dynamics that serve to coordinate the R, O and S components. For example, propagating fMRI activity may reflect propagating LFPs (Thompson et al., 2014). The rotational dynamics of traveling waves and cortical spirals (clockwise, anti-clockwise) might drive general phases of language comprehension and production (e.g., listening vs. speaking; Xu et al., 2023), with more specific parsing stages being coordinated by the postulated mechanisms underlying O and S.

Overall, the E component is motivated by the recent consensus that inter-areal coherence measures are better predictors of working memory performance than single-area spiking or LFP activity (Rezayat et al., 2022).

9. Causal evidence

This section will explore current evidence that the neural architecture outlined here for ROSE may have some causal-explanatory power.

Beginning with the basic components of ROSE, we cannot directly claim that LFPs ‘do’ computation; their activity seems to index some underlying code that remains elusive in its formal character and neurochemical basis. Yet, aspects of brain dynamics have recently been associated with causal disruptions in cognitive and perceptual functions. A general guiding question that neurolinguists should consistently ask is the following: ‘Is this signal important for the brain, or is it important for the neuroscientist?’ There are many possible neural signals to record and make theoretical claims about, but a systemic means for adjudicating between correlation and causation remains a difficult obstacle. Nevertheless, some directions are opening up for establishing the causal role of oscillations.

As Snyder (2015) reviews, oscillations are increasingly being shown to play a causal, and not correlational, role in the perceptual segregation of sound patterns. Riecke et al. (2018) used speech-envelope-shaped transcranial current stimulation to conduct two experiments involving a cocktail party-like scenario and a listening situation devoid of any speech-amplitude envelope input. The results suggest effects on listeners’ speech recognition performance, implying the existence of a causal role for speech-brain entrainment. More generally, oscillatory dynamics have been shown to play a causal role in modulating effective neuronal connectivity (Galuske et al., 2019). Recent work has shown that phase-amplitude coupling between physiologic high frequency γ and low frequency δ is strengthened during development (Asano et al., 2023), although further work is needed to explore the broader functional implications of this process (the authors only explore visual memory consolidation, and not natural language).

With respect to the present traveling waves architecture, some preliminary evidence from Mesnildrey et al. (2023) looking at language production in healthy controls and individuals with aphasia suggests that both phase and amplitude traveling waves contribute to the synchronization and communication between distinct brain regions, and that cortical traveling wave dynamics are impacted by the presence of brain lesions. Relatedly, causal studies indicate that manipulating synchrony between brain areas can influence working memory task performance (Rezayat et al., 2022), supporting the above proposals concerning E.

Moving closer to our concerns, Riddle et al. (2020) provide causal evidence from TMS that θ is involved in the control of working memory. That δ - β and θ - γ coupling are also causally involved in cognitive control (Riddle et al., 2021) suggests that phase-amplitude coupling can be used as a neurocomputational algorithm for feature extraction and association. Other research using hippocampal-targeted TMS-fMRI points to the causal role of θ - γ nested oscillations in memory encoding (Hermiller et al., 2020). θ has a causal role in spatial memory re-play (Zielinski et al., 2020). Fernández-Ruiz et al. (2019) looked at the rat brain and showed that learning and correct recall in spatial memory tasks are associated with extended sharp wave ripples. Artificially prolonging these ripples improved working memory performance, suggesting again a causal role for these rhythms in representational maintenance, at least over these specific neural populations. There also appears to be a causal role for α oscillations in perceptual binding (Zhang et al., 2019).

Regardless, as noted by Earl K. Miller, questions about the causal role of oscillations could also be asked of spikes. Both are signals that work together, and decoupling them seems difficult. Dismissing observed signals as ‘epiphenomenal’ without showing how, or why, does little to advance the neurobiology of cognition (Krakauer, 2022). Indeed, claims like ‘X is epiphenomenal’ are often synonymous with ‘X does not fit my theory’, as Miller has noted. It is also difficult to imagine what the alternative would be for the brain to implement complex computations and goal-directed behavior. Rhythmic fluctuations provide the foundations for these systems almost for free. Coordinating a large number of gates across a huge number of neurons seems impossible without this mechanism. That said, it is worth noting here that the frequency bands invoked in ROSE should not be seen as *types*, or fixed bounds for computation, but rather *tokens* of computation that are physiologically bound over brain maturation and development.

Following the chain of processes intrinsic to ROSE, I assume here that single-unit and assembly representations coding for discrete semantic and formal syntactic features would act as the spark igniting the neurocomputational architecture of the model. This would trigger LFP-scaled operations such as feature composition and sensorimotor transformations (grapheme-to-phoneme transitions, etc.), which in turn would be regulated by low frequency coordination of spike-LFP synchronization, and cross-regional synchronization via migrating waves of δ - θ coupling. An emerging consensus in this general direction is that spike-related activity is also present in low frequency activity, as well as in the γ band (Buzsáki et al., 2012; Łęski et al., 2013). Under ROSE, each scale of representation and computation can mechanistically be linked to the next. This departs from other current models that attempt, for example, to ground N400 ERP effects directly from single-unit responses, with no causal-explanatory mechanism linking them (Samimizad et al., 2022).

By assessing this causal evidence, alongside a neural code for syntax, it is my hope that ROSE can fulfil van Bree’s (2023) criteria for a mechanistic account of cognition, moving beyond localization and delivering a proposal for how organized interactions between

parts explains basic language structure (for an excellent overview of the relationship between experimental psycholinguistics and neuroscientific evidence, see [van der Burght et al., 2023](#)). More focus on algorithmic/parsing details will be needed in future work, since although ROSE provides a specific mechanistic basis I have intentionally kept to minimal compositional schemes here, leaving aside more complex parsing stages.

10. The fallen leaves tell a story: Prospects for ROSE

“[W]e run the risk of being able to measure every cell (or subcellular component even) in the brain in a theoretical vacuum.”
([Pessoa, 2023](#), p. 358)

This article proposed a new neurocomputational architecture for natural language, termed ROSE (Representation, Operation, Structure, Encoding). Although I have been concerned here with the “basic property” ([Chomsky, 2021](#)) of syntactic structure building (MERGE and its affiliate interface processes), future research should more concretely map complex syntactic processes, such as pronominal binding and *wh*-movement, to various stages of the interactions between the components of ROSE.

Importantly, while one researcher may be inclined to pursue accounts of relating generative grammar or minimalist parsing processes to ROSE, other researchers may argue for relations between the components of ROSE and other psycholinguistic models of language. It may turn out that minimalist grammar accounts, for example, have a more difficult time relating R with O, and O with S, than other accounts. For example, [Stanojević et al. \(2021\)](#) examine the derivations assigned by a near-context free formalism, Combinatory Categorical Grammar (CCG). CCG improves BOLD signal modeling in six language-relevant brain regions, and including a parsing step facilitating late-attachment of modifier phrases improves the fit in anterior temporal and inferior frontal cortices. Meanwhile, other researchers ([Brennan et al., 2016](#); [Li & Hale, 2019](#)) discovered that node counts on X-bar structures derived by minimalist grammars predict unique variance in BOLD signal in the posterior temporal lobe, whereas dependency grammars (emphasizing relational syntactic information between a head and its dependent) show effects in middle temporal pole ([Lopopolo et al., 2021](#)). Given that basic structure-building mechanisms are associated under ROSE as originating in posterior temporal cortex, and that extra-syntactic processing stages commonly implicate inferior frontal cortex and the temporal pole, these joint results may suggest that different grammatical theories can capture varying aspects of sentence processing complexity (basic MERGE vs. late parsing stages and dependencies).

The basic philosophy underlying ROSE is that mesoscale neural organization can be useful for brain function ([Pinotsis et al., 2023](#)), and that high frequency γ oscillations report mechanisms and underlying communication channels of neural computations ([Fernández-Ruiz et al., 2023](#)). Neural oscillations organize cortical activity to produce computation ([Lundqvist et al., 2023](#)), and ROSE builds an architecture for syntax that presupposes this. Some exciting prospects for testing ROSE come in the form of multi-channel recordings with broad cortical access using planar microelectrode arrays, implanted intracortically during awake brain surgery. These have recently been used to unveil traveling waves and also single-unit responses indexing basic mathematical operations in brain tumor patients in lateral parietal cortex ([Eisenkolb et al., 2022](#)). Both high γ power and the speed of traveling waves were greater when processing higher numerosities. Scaling from single-units to traveling waves would permit a comprehensive language mapping of the kind needed to test and refine ROSE. Other new implantable probes include DISC arrays ([Abrego et al., 2023](#)), which carry great promise for detecting unit activity in healthy perisylvian language cortex. As the terra firma of traditional neuroimaging methods remain incapable of confidently separating responses from transient dynamical processes such as syntax, semantics and lexicality, the terra incognita of emerging intracranial recording devices will likely provide new insights into cortical computation.

The inherently dynamical architecture of ROSE is also compatible with a recent, provocative assessment from [Aliko et al. \(2023\)](#), who argue that classical frontotemporal language regions should be re-conceived as dynamic connectivity hubs that regulate interactions across widespread brain regions responsible for parsing distinct features of language. This emphasis on whole-brain distributions of networks and their coordination, in combination with the existence of smaller-scale cortical mosaics for linguistic meaning (see above), conspire to support ROSE.

Brain models informed by computational concerns will continue to be needed in the neurosciences, in particular as we approach the advent of widespread availability of single-unit human recordings ([Rust & LeDoux, 2023](#)). This (partially) ‘outside-in’ perspective has been critiqued recently. [Buzsáki \(2019\)](#) advocates for an inside-out perspective on building neural models of cognition, and considers the classical Marrian framework a purely outside-in perspective. Yet, Marr himself stressed that the three levels should be investigated in parallel, not necessarily prioritizing any given level (see also [Marcus, 2001](#)). But this is a balancing act: too much outside-in, and we will soon get claims about ‘Neo-Davidsonian existential closure neurons’; too much inside-out, and we will receive calls to dismantle models of sentence parsing. Regardless of one’s philosophical bent, single-unit and other types of intracranial recordings are plainly the most direct and reliable means to further test and refine ROSE ([McCarty et al., 2022](#)), in particular given recent independent assessments that spontaneous BOLD activity may be more closely aligned with offline plasticity and homeostatic processes than online fluctuations in cognitive content ([Laumann & Snyder, 2021](#)), and sceptical editorial commentary from major journals concerning the validity of fMRI: “[I]t is extremely difficult to conclude that functional connectivity as measured by functional MRI genuinely measures information exchange between brain regions” ([Kullmann, 2020](#), p. 1045; but see also [Esfahlani et al., 2020](#); [Toi et al., 2022](#)).

In a discussion of some neural mechanisms integral to ROSE, [Coopmans et al. \(2023\)](#) write that cross-frequency coupling “relies on a neurobiological model of sequence encoding, which represents ‘horizontal’ information about ordinal positions in a sequence. However, what matters for hierarchical syntax is the ‘vertical’ relation between a constituent and its subordinate elements”. But as [Kazanina and Tavano \(2023c\)](#) point out, sequence order is not the only possible read-out of phase coding. For our purposes, grammatical rules pertaining to labeling are equally as plausible. For example, even though a given θ - γ cycle provides a linear sequence of

items, with ROSE it is the accessing of this information by independent, traveling waves (e.g., linked to a δ - θ complex) that imposes biases on how this information is read out over frontotemporal language sites. And as [Martorell et al. \(2023\)](#) comprehensively review, echoing many others, phase-amplitude coupling provides a feasible means for syntactic information (phase encoded) to interface with lexico-semantic information (power encoded), generating basic linguistic structure ([Murphy, 2015b; 2020a](#)).

It is common to object to these kinds of theoretical proposals by branding them a crude form of ‘direct mapping’, or ‘isomorphism’. ROSE continues this crude tradition by establishing an even more explicit isomorphism between system-level complexity and syntactic complexity (e.g., cells and syntactic features vs. global coherence and phrase structure). Alternative accounts that build syntactic operations into neural systems of diverging levels of structural complexity have not been forthcoming, to my knowledge, but would naturally be required to establish any kind of adversarial collaborations and experimental testing of these models. Through this, it would be possible to pit different candidate neural mechanisms for syntax against one another and compare effect sizes across studies ([van Bree, 2023](#)), to see which mechanism – from ROSE and other models – best explains real-time direct cortical effects of language processing.

More broadly, ROSE is sympathetic to recent moves in philosophy of biology to view a range of biological constructs as processes rather than objects ([Nicholson and Dupré, 2018](#)). ROSE is built entirely from neurocomputational mechanisms that are already known to subservise clusters of generic perceptual and cognitive operations. As [Hasson et al. \(2018\)](#) note, many language-specific interpretations of experimental neurophysiological and electrophysiological data might be better seen as implementations of highly generic processes, like monotonic integration of information, establishment of coherence, prediction, and representational binding.

As recently noted, current theories that model hierarchical structure building via low frequency dynamics “[correlate] some neural measure with attributes of a hierarchical syntactic structure and thus [concern] the outcome of syntactic structure construction” ([Kazanina & Tavano, 2023b](#)). By initiating syntactic structure building at the cellular R level, and accounting for these ‘output’ low frequency responses at the S and E levels, the ROSE architecture goes beyond current accounts that are more closely tied to the output of structure building rather than its initial generation.

Nevertheless, ROSE needs to be developed further in order to more clearly accommodate relational syntactic information, of the kind found with long-distance dependency resolution (for critical discussion, see [Tavano et al., 2023](#)). Currently, ROSE provides an explicit architecture for vertical syntactic information on a basic phrasal level, but further empirical and theoretical advances are needed to test how to accommodate these more complex features of syntax.

Questions that remain concern the precise cortical infrastructure of ROSE, and how best to establish a mathematically rigorous algorithmic architecture. For example, superficial cortical layers oscillate at faster frequencies, and deeper layers at slower frequencies, potentially due to different interneurons (e.g., FS-PV vs. SOM) ([Neske & Connors, 2016](#)), while superficial layers are sources of feed-forward structural connections, and deeper layers are sources of feed-back connections ([Mendoza-Halliday et al., 2022](#)). At the same time, the relation between these remains unclear since increases in high γ power are not always found alongside decreases in low frequency power; this depends on cortical region ([Fellner et al., 2019](#)). Testing ROSE further would also require a better understanding of the relationship between single-unit activity and cerebral blood volume, in order to more confidently relate extracranial imaging (e.g., fMRI) and electrophysiology (see [Claron et al., 2023](#) for the first steps in this direction).

Testing ROSE could provide specific insights into evolutionary debates, concerning which cortical regions should be subject to investigation as to their evolutionary novelties (cellular profile, connectomics, etc.). For example, [Friederici \(2023\)](#) assesses “an evolutionary expansion of Broca’s region in the human brain” which she speculates as providing “additional space needed for the neural representation of language in humans” (see also [Boeckx, 2023](#)). With ROSE, we can weigh up options as to the specific type of space this might be relevant to, i.e., syntactic working memory (E) vs. MERGE-specific computations (S).

Moving to a related concern, a reviewer asks if the oscillatory patterns in ROSE reflect language-specific computations. In terms of the architectural implications, my suggestion is that each of the four components of ROSE are to be found separately in non-linguistic cognitive domains (e.g., musical cognition builds structures, navigation requires encoding, mathematics requires representations), and that the ROSE architecture for language can potentially build testable hypotheses for other domains. The domain-specificity of ROSE arrives with the format of the representations, the richness of structures built (e.g., δ coupled with θ but also γ , over the same rapid time window) and the specific regional engagement that traveling waves propagate to.

Another point worth highlighting is that the ROSE architecture is hypothesized to take scope over all human languages, including many understudied languages in neurolinguistics ([Malik-Moraleda et al., 2022](#)). Indeed, by not relying on aspects of temporal ordering, a related strength of the model is that it should also accommodate gestural language. This domain is one of the more intriguing directions for experimental research, since in principle the same neurocomputational architecture that ROSE proposes for auditory and orthographic systems should also obtain for other modalities.

11. Conclusion

“Words weigh now no more to him than raindrops to Rethfernhim.” ([Joyce, 2012](#), p. 74)

The development of the present ROSE architecture comes partly in response to the current absence of oscillatory phase coding in models of natural language syntax. This absence is growing increasingly stark given that this mechanism has long been known to be computationally useful in executing rapid neural binding. Many researchers who have kept to frameworks emerging purely from MEG-derived event-related fields, scalp EEG-derived event-related potentials, and fMRI-derived BOLD responses have begun to lose hope in the possibility of finding the neural basis of syntax, but have done so without moving beyond the limitations of their scale of analysis or recording, or linking hypotheses. [Pylkkänen \(2019\)](#) writes that “[t]he neuroscience-of-language field has long assumed that our brains

build syntactic structure during language processing. Today, it is reasonable to question this assumption". She reasonably speculates that, based on the evidence reviewed in her article, something like MERGE might not be an obvious neural operation, or, alternatively, it might not to be found in presently-explored neural signals. I hope to have shown via ROSE that these candidate neural signals do in fact exist, and can be readily investigated in the manner outlined above. While a recent meta-analysis of fMRI and PET studies of language processing found no support for clear syntax-specific regions (Turker et al., 2023) – although this study did support a clear role for left IFG, left pMTG and left pSTG in syntax – under ROSE the rapid electrophysiological signatures detected via direct cortical recordings provide a more promising direction.

Under ROSE, there is no sense to be made out of claims that syntax (a complex series of operations and representations) lies in one specific brain region. Each level of linguistic representation and structure-building requires its own suitable scale of neural organization, not just cartographic mapping. In this respect, one goal for the future would be to refine our understanding of the principled links between each of the four components of ROSE (i.e., how R mechanistically maps to O, and O to R), since this forms the crux around which the distinct scales of system complexity can be most directly tested and falsified. For instance, the line between 'oscillation or not' can sometimes be blurred, with a leaky integrate-and-fire model being both an oscillator and a model of evoked responses, and there is also heterogeneity in the possible mechanisms for oscillations (Doelling & Assaneo, 2021), and hence how they relate to single-unit information sources. At the same time, oscillations do in fact display some unique properties, such as their eigenfrequency, their Arnold Tongue, or their independence of rhythmic stimulus (their 'echo') (Fröhlich, 2015; van Bree et al., 2022). Many possible candidates for linking the four ROSE components exist once we refine our biophysical models of oscillations.

To add another point of testability, one of the basic predictions that emerges directly from ROSE concerns category-related discriminability. For instance, at the level of single units one would predict very clear category-related discrimination in the effects for nominals versus verbs, or between different types of nominals that differ in their underlying featural specifications. However, as we increase in the scale of neural system complexity, so too would we expect that category-specific discriminability would be less successful. As such, ROSE predicts that while we would be able to successfully ascertain if a given set of traveling waves were encoding sentential information versus pseudoword information, we would likely be unable to discriminate if the same set encoded information about nominals of type P or type Q (e.g., mass vs. count nouns). Many other such empirical predictions can be derived directly from ROSE. A more direct test of the R component would demand a linking of LFP recording to cellular but also molecular level imaging.

Another direction for future work concerns relating the predictions of ROSE to the use of recurrent neural network grammars (RNNG) via intracranial recordings, expanding beyond existing work utilizing fMRI. For example, Sugimoto et al. (2023) report robust effects of left-corner syntactic parsing in left inferior frontal and temporo-parietal regions using RNNGs. This left-corner RNNG outperformed both an RNNG that utilizes top-down parsing and also a sequential long-short term memory (LSTM) network (their RNNGs were bidirectional LSTMs with additional Markovian enhancements). Going beyond localization of this type of parsing sensitivity to exploring the precise neural scale of RNNG performance would allow for direct testing of ROSE.

In terms of their roles in shaping information processing in cognition, the currently identified frequency-specific mechanisms seem to align with an emerging consensus that slow frequencies control input sampling, α/β gate information flow, and high frequency activity is controlled by slower rhythms (ElShafei et al., 2022). Moving beyond this, a newly emerging focus on brain criticality (O'Byrne & Jerbi, 2023), and how this concept might relate to brain rhythms, provides exciting avenues for future work in theoretical neurolinguistics.

The philosophical foundations of ROSE, briefly touched on here, are also in line with research documenting the rich array of innate capacities utilized during language acquisition in neonates, who can distinguish distinct phonemes, detect word boundaries, learn words and track phrasal structures and even larger discourse units (Kujala, Partanen, et al., 2023).

Currently, due to the lack of consensus regarding how to ground syntactic combinatorics and lexicality in the brain, researchers enjoy many degrees of freedom when selecting from their preferred linguistic theory, processing theory and neurobiological framework (van der Burght et al., 2023). In proposing ROSE, I hope to further constrain this landscape, narrowing the space of likely candidate neural mechanisms for syntactic structure building, and also the space of suitable neural recording measures based on the level of linguistic structure that one is investigating.

Research into this topic may progressively validate the present assignment of linguistic constructs to particular scales of neural organization. Alternatively, it may ultimately transpire that the foundational structures of natural language syntax are not to be found at any of these scales, and will instead remain at a remote distance to modern science, lost to us on "the wide fathomless sea of living existence" (Montgomery, 1886, p. 574).

Funding

This work was supported by the National Institute of Neurological Disorders and Stroke (NS098981).

Declaration of competing interest

The author declares no conflicts of interest.

Data availability

No data was used for the research described in the article.

Acknowledgements

My thanks to all members of the Tandon Lab at the Department of Neurosurgery, UTHealth, including Nitin Tandon, Oscar Woolnough, Meredith McCarty, Kathryn Snyder, Tessy Thomas, Aditya Singh, Patrick Rollo and Kiefer Forseth. My thanks go to Patrick Trettenbrein for insightful comments of an earlier draft, and to Juan Uriagereka for helpful comments on the model. I also wish to thank Antonio Benítez-Burraco, Karl Friston, Koji Hoshi, Evelina Leivada, Gary Marcus and Jae-Young Shim for their more recent collaborative efforts with me, who have helped shape my understanding of the limits of the neurolinguistic enterprise, and who have each directly influenced the framing of at least one of the four components of the model presented here. I also wish to thank the anonymous reviewers for providing valuable insights into improving the structure and argumentation of this work.

Appendix. Glossary of Terms

Agreement: When the form of a word/morpheme covaries with that of another word or phrase. Compare ‘John runs to the park’ with ‘We run to the park’, where the form of the verb is conditioned by whether the noun is singular or plural.

Bottom-up/Top-down processing: The use of lower-level, perceptual processing (bottom) vs. the use of existing, prior knowledge and representations to derive inferences.

Binding theory: A set of principles accounting for the distribution of anaphoric elements (e.g., pronouns). A pronoun, or ‘bindee’, typically has an antecedent, or ‘binder’, as in ‘John said he was happy’, where the pronoun can successfully refer to the noun, unlike in ‘*He said John was happy’.

Brodman area (BA): A region of the cortex defined by its cytoarchitectonics, or cell structure.

C-command: An expression of the relationship between nodes on a hierarchically organized syntactic tree. If a node has any ‘sibling’ nodes (nodes which are dominated by the same node) then it c-commands them, and if not then it c-commands every node that its dominating ‘parent’ node c-commands.

Cell assembly: A network of functionally connected neurons that is activated by a particular mental process and whose excitatory connections have been strengthened in time.

Content word: Words which name objects and their qualities. These are typically nouns but can also be verbs, adjectives and adverbs.

Cross-frequency coupling: When interactions between discrete frequency bands give rise to more complex regulatory structures. For instance, phase-amplitude coupling denotes the statistical dependence between the phase of a low-frequency band and the amplitude of a high-frequency band.

Embedding: The ability for a linguistic unit to host within it another linguistic unit.

Erdős-Rényi network: A random graph where each possible edge has the same probability p of existing, and the degree of a node i (k_i) is defined as the number of connections it has to other nodes. The degree distribution $P(k)$ of the network is a binomial distribution, decaying exponentially for large degrees k , permitting only small degree fluctuations. Facilitates coupling between slow frequency components.

Function word: Words denoting grammatical relationships between content words, such as prepositions, pronouns and conjunctions.

Gain modulation: How neurons nonlinearly combine information from multiple sources.

Generative grammar: The branch of linguistics which assumes that natural language is a mental computational system of rules generating an unbounded array of hierarchically structured expressions, with varying degrees of acceptability.

Labeling: The categorization of a MERGE-generated object at the point of conceptual interpretation, providing an asymmetric syntactic identity based on which element is most structurally prominent and easiest to search for, e.g., Z in $WS = \{Z, \{X, Y\}\}$.

MERGE: The computational operation which selects two objects from the lexicon, α and β , and forms an unordered set mapping them to an active workspace, $WS = \{\alpha, \beta\}$.

Oscillation: The unfolding of repeated events in terms of frequency. In the context of the brain, neural oscillations (or brain rhythms) are repetitive patterns of activity caused by excitatory and inhibitory cycles in cell assemblies.

Phase-locking/synchronization: When multiple cyclic signals oscillate such that their phase angles stand in a systematic relation.

Phi-feature (ϕ): Linguistic features of Person, Number and Gender.

Phonology: The system of sound, or a set of sound-related features and rules stipulating how these features interact in a given language.

Recursion: The hallmark of natural language syntax; when a linguistic rule can be applied to the result of the application of the same rule, creating, for instance, ‘nested’ structures like ‘John, who likes Sarah, will come to the party’ from ‘John will come to the party’.

Syntax: Informally termed the ‘grammar’, this is the set of principles governing the structure of morphologically complex word-like elements, phrases and sentences, and their combinatorial processes.

Traveling waves: Oscillations which migrate in phase coherence across the brain, whereby the spiking of neural clusters is coordinated not just across two fixed points but across a particular extended path.

Vector code: A means to represent specific features or attributes of sensory stimuli, cognitive processes, or motor actions as patterns of neural activity in the brain. Vectors have both magnitude and direction, and can be used to represent various types of information in a multidimensional space.

Word movement: A core concept in generative grammar whereby syntactic objects are displaced from the position where certain

of their features are interpreted.

References

- Abraham, W. C., Jones, O. D., & Glanzman, D. L. (2019). Is plasticity of synapses the mechanism of long-term memory? *Npj Science of Learning*, 4, 1–10.
- Abrego, A. M., Khan, W., Wright, C. E., Islam, M. R., Ghajar, M. H., Bai, X., Tandon, N., & Seymour, J. P. (2023). Sensing local field potentials with a directional and scalable depth electrode array. *Journal of Neural Engineering*, 20(1), Article 016041.
- Adger, D. (2017). *A memory architecture for merge*. Ms. Queen Mary University of London. ling.auf.net/lingbuzz/003440.
- Ahmadi, N., Constandinou, T. G., & Bouganis, C.-S. (2021). Robust and accurate decoding of hand kinematics from entire spiking activity using deep learning. *Journal of Neural Engineering*, 18(2), Article 026011. <https://doi.org/10.1088/1741-2552/abde8a>
- Alamia, A., & VanRullen, R. (2023). A traveling waves perspective on temporal binding. *Journal of Cognitive Neuroscience*. https://doi.org/10.1162/jocn_a_02004
- Aliko, S., Wang, B., Small, S. L., & Skipper, J. I. (2023). The entire brain, more or less, is at work: 'language regions' are artefacts of averaging. *bioRxiv*. <https://doi.org/10.1101/2023.09.01.555886>
- Alyahya, R. S. W., Halai, A. D., Conroy, P., & Lambon Ralph, M. A. (2018). Noun and verb processing in aphasia: behavioural profiles and neural correlates. *NeuroImage: Clinical*, 18, 215–230.
- Anderson, A. J., Kiela, D., Binder, J. R., Fernandez, L., Humphries, C. J., Conant, L. L., et al. (2021). Deep artificial neural networks reveal a distributed cortical network encoding propositional sentence-level meaning. *Journal of Neuroscience*, 41(18), 4100–4119.
- Arnulfo, G., Wang, S. H., Myrov, V., Toselli, B., Hirvonen, J., Fato, M. M., et al. (2020). Long-range phase synchronization of high-frequency oscillations in human cortex. *Nature Communications*, 11, 5363.
- Artoni, F., d'Orio, P., Catricala, E., Conca, F., Bottoni, F., Pelliccia, V., ... Moro, A. (2020). High gamma response tracks different syntactic structures in homophonous phrases. *Scientific Reports*, 10, 7537.
- Asano, E., Sakakura, K., Kuroda, N., Sonoda, M., Mitsuhashi, T., Firestone, E., et al. (2023). Developmental atlas of phase-amplitude coupling between physiologic high-frequency oscillations and slow waves. *Research Square*. <https://doi.org/10.21203/rs.3.rs-2799931/v1>
- Assem, M., Hart, M. G., Coelho, P., Romero-Garcia, R., McDonald, A., Woodberry, E., et al. (2023). High gamma activity distinguishes frontal cognitive control regions from adjacent cortical networks. *Cortex*, 159, 286–298.
- Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory*, 8 pp. 47–89). New York: Academic Press.
- Baggio, G. (2018). *Meaning in the brain*. Cambridge, MA: MIT Press.
- Baggio, G., & Hagoort, P. (2011). The balance between memory and unification in semantics: A dynamic account of the N400. *Language & Cognitive Processes*, 26(9), 1338–1367.
- Bahramsharif, A., Jensen, O., Jacobs, J., & Lisman, J. (2018). Serial representation of items during working memory maintenance at letter-selective cortical sites. *PLoS Biology*, 16(8), Article e2003805.
- Bahramsharif, A., Mazaheri, A., Levar, N., Schuurman, P. R., Figeo, M., & Denys, D. (2016). Deep brain stimulation diminishes cross-frequency coupling in obsessive-compulsive disorder. *Biological Psychiatry*, 80(7), e57–e58.
- Bao, P., She, L., McGill, M., & Tsao, D. (2020). A map of object space in primate inferotemporal cortex. *Nature*, 583, 103–108.
- Barack, D. L., & Krakauer, J. W. (2021). Two views on the cognitive brain. *Nature Reviews Neuroscience*, 22, 359–371.
- Bartoli, E., Bosking, W., Chen, Y., Li, Y., Sheth, S. A., Beauchamp, M. S., et al. (2019). Functionally distinct gamma range activity revealed by stimulus tuning in human visual cortex. *Current Biology*, 29(20), 3345–3358.
- Bastiaansen, M., Magyari, L., & Hagoort, P. (2010). Syntactic unification operations are reflected in oscillatory dynamics during on-line sentence comprehension. *Journal of Cognitive Neuroscience*, 22(7), 1333–1347.
- Bastos, A. M., Vezoli, J., Bosman, C. A., Schoffelen, J.-M., Oostenveld, R., Dowdall, J. R., et al. (2015). Visual areas exert feedforward and feedback influences through distinct frequency channels. *Neuron*, 85(2), 390–401.
- Becker, R., & Hervais-Adelman, A. (2023). Individual theta-band cortical entrainment to speech in quiet predicts word-in-noise comprehension. *Cerebral Cortex Communication*. <https://doi.org/10.1093/texcom/tgad001>. tgad001.
- Benitez-Burraco, A., & Murphy, E. (2019). Why brain oscillations are improving our understanding of language. *Frontiers in Behavioral Neuroscience*, 13, 190.
- Bhattacharya, S., Brincat, S. L., Lundqvist, M., & Miller, E. K. (2022). Traveling waves in the prefrontal cortex during working memory. *PLoS Computational Biology*, 18(1), Article e1009827.
- Bhattacharya, S., Donoghue, J. A., Mahnke, M., Brincat, S. L., Brown, E. N., & Miller, E. K. (2022). Propofol anesthesia alters cortical traveling waves. *Journal of Cognitive Neuroscience*, 34(7), 1274–1286.
- Bhaya-Grossman, I., & Chang, E. F. (2022). Speech computations of the human superior temporal gyrus. *Annual Review of Psychology*, 73, 79–102.
- Bi, Y., Wang, X., & Caramazza, A. (2016). Object domain and modality in the ventral visual pathway. *Trends in Cognitive Sciences*, 20(4), 282–290.
- Boeckx, C. (2023). What made us "hunter-gatherers of words". *Frontiers in Neuroscience*, 17, Article 1080861.
- Bonfond, M., & Jensen, O. (2015). Gamma activity coupled to alpha phase as a mechanism for top-down controlled gating. *PLoS One*, 10(6), Article e0128667.
- Bošković, Z. (2021). *Merge, move, and contextuality of syntax: The role of labeling, successive-cyclicity, and EPP effects*. Ms. University of Connecticut.
- Botvinick, M., & Watanabe, T. (2007). From numerosity to ordinal rank: A gain-field model of serial order representation in cortical working memory. *Journal of Neuroscience*, 27(32), 8636–8642.
- van Bree, S. (2023). A critical perspective on neural mechanisms in cognitive neuroscience: Towards unification. *Perspectives on Psychological Science*. <https://doi.org/10.1177/17456916231191744>
- van Bree, S., Alamia, A., & Zoefel, B. (2022). Oscillation or not—why we can and need to know (commentary on Doelling and Assaneo, 2021). *European Journal of Neuroscience*, 55(1), 201–204.
- van Bree, S., Sohoglu, E., Davis, M. H., & Zoefel, B. (2021). Sustained neural rhythms reveal endogenous oscillations supporting speech perception. *PLoS Biology*, 19(2), Article e3001142.
- Brennan, J. R., Dyer, C., Kuncoro, A., & Hale, J. T. (2020). Localizing syntactic predictions using recurrent neural network grammars. *Neuropsychologia*, 146, Article 107479.
- Brennan, J. R., & Martin, A. E. (2020). Phase synchronization varies systematically with linguistic structure composition. *Philosophical Transactions of the Royal Society B*, 375, 1791.
- Brennan, J. R., Stabler, E. P., Van Wagenen, S. E., Luh, W. M., & Hale, J. T. (2016). Abstract linguistic structure correlates with temporal activity during naturalistic comprehension. *Brain and Language*, 157–158, 81–94.
- Bressler, S. L., & Kelso, J. A. (2001). Cortical coordination dynamics and cognition. *Trends in Cognitive Sciences*, 5, 26–36.
- Brincat, S. L., Donoghue, J. A., Mahnke, M. K., Kornblith, S., Lundqvist, M., & Miller, E. K. (2021). Interhemispheric transfer of working memories. *Neuron*, 109(6), 1055–1066.
- Bucher, D., Taylor, A. L., & Marder, E. (2006). Central pattern generating neurons simultaneously express fast and slow rhythmic activities in the stomatogastric ganglion. *Journal of Neurophysiology*, 95, 3617–3632.

- van der Burght, C. L., Friederici, A. D., Maran, M., Papitto, G., Pyatigorskaya, E., Schroën, J. A. M., Trettenbrein, P. C., & Zaccarella, E. (2023). Cleaning up the brickyard: How theory and methodology shape experiments in cognitive neuroscience of language. *Journal of Cognitive Neuroscience*. https://doi.org/10.1162/jocn_a_02058
- Burroughs, A., Kazanina, N., & Burroughs, C. (2021). Grammatical category and the neural processing of phrases. *Scientific Reports*, *11L*, 2446.
- Buschman, T., & Miller, E. K. (2023). Working memory is complex and dynamic, like your thoughts. *Journal of Cognitive Neuroscience*, *35*(1), 17–23.
- Buzsáki, G. (2004). Large-scale recording of neuronal ensembles. *Nature Neuroscience*, *7*, 446–451.
- Buzsáki, G. (2019). *The brain from inside out*. Oxford: Oxford University Press.
- Buzsáki, G., Anastassiou, C. A., & Koch, C. (2012). The origin of extracellular fields and currents – EEG, ECoG, LFP and spikes. *Nature Reviews Neuroscience*, *13*, 407–420.
- Bybee, B., Belsten, A., & Sommer, F. (2022). Cross-frequency increases memory capacity in oscillatory neural networks. In *Poster presented at neuroscience 2022 (society for neuroscience annual meeting)*, november 12–16.
- Cai, J., Jamali, M., Kfir, Y., Belinkov, Y., Paulk, A., Cash, S., & Williams, Z. (2022). Single neuronal decoding of human speech processing: A deep learning approach. In *Poster presented at neuroscience 2022 (society for neuroscience annual meeting)*, november 12–16.
- Chalas, N., Daube, C., Kluger, D. S., Abbasi, O., Nitsch, R., & Gross, J. (2023). Speech onsets and sustained speech contribute differentially to delta and theta speech tracking in auditory cortex. *Cerebral Cortex bhac*, *502*. <https://doi.org/10.1093/cercor/bhac502>
- Chan, A. M., Halgren, E., Marinkovic, K., & Cash, S. S. (2011). Decoding word and category-specific spatiotemporal representations from MEG and EEG. *NeuroImage*, *54*(4), 3028–3039.
- Chiou, R., Jeffries, E., Duncan, J., Humphreys, G. F., & Lambon Ralph, M. A. (2022). A middle ground where executive control meets semantics: The neural substrates of semantic control are topographically sandwiched between the multiple-demand and default-mode systems. *Cerebral Cortex*, *33*(8), 4512–4526.
- Chomsky, N. (Forthcoming). Genuine explanation. G. Bocci, D. Botteri, C. Manetti and V. Moscati (Eds.). *Issues in comparative morpho-syntax and language acquisition*.
- Chomsky, N. (1957). *Syntactic structures*. The Hague: Mouton de Gruyter.
- Chomsky, N. (1967). The formal nature of language. In E. Lenneberg (Ed.), *Biological foundations of language* (pp. 397–442). New York: Wiley and Sons.
- Chomsky, N. (1974). *The amherst lectures*. University of Paris VII.
- Chomsky, N. (2000). *New horizons in the study of language and mind*. Cambridge: Cambridge University Press.
- Chomsky, N. (2021). Minimalism: Where we are now, and where we can hope to go. *Gengo Kenkyu*, *160*, 1–41.
- Chomsky, N. (2023). Genuine explanation and the strong minimalist thesis. *Cognitive Semantics*, *8*(3), 347–365.
- Chomsky, N., Gallego, Á. J., & Ott, D. (2019). Generative grammar and the faculty of language: Insights, questions, and challenges. In Á. J. Gallego, & D. Ott (Eds.), *Generative syntax: Questions, crossroads, and challenges. Special issue of Catalan journal of linguistics* (pp. 226–261).
- Chomsky, N., Seely, T. D., Berwick, R. C., Fong, S., Huybregts, M. A. C., Kitahara, H., McInerney, A., & Sugimoto, Y. (2023). *Merge and the strong minimalist thesis. Elements in generative syntax*. Cambridge: Cambridge University Press.
- Chuderski, A. (2016). Fluid intelligence and the cross-frequency coupling of neuronal oscillations. *Spanish Journal of Psychology*, *19*(e91), 1–13.
- Claron, J., Provansal, M., Salaridaine, Q., Tissier, P., Dizeux, A., Deffieux, T., et al. (2023). Co-variations of cerebral blood volume and single neurons discharge during resting state and visual cognitive tasks in non-human primates. *Cell Reports*, *42*(4), Article 112369.
- Cohen, P. (2002). The origins of protein phosphorylation. *Nature Cell Biology*, *4*(5), E127–E130.
- Comeaux, P., Clark, K., & Noudoost, B. (2023). A recruitment through coherence theory of working memory. *Progress in Neurobiology*, *228*, Article 102491.
- Coopmans, C. W., Hoop, H. D., Hagoort, P., & Martin, A. E. (2022). Effects of structure and meaning on cortical tracking of linguistic units in naturalistic speech. *Neurobiology of Language*, *2*(3), 386–412.
- Coopmans, C. W., Mai, A., Slaats, S., Weissbart, H., & Martin, A. E. (2023). What oscillations can do for syntax depends on your theory of structure building. *Nature Reviews Neuroscience*. <https://doi.org/10.1038/s41583-023-00734-5>
- Daniele, A., Giustolisi, L., Caterina Silveri, M., Colosimo, C., & Gainotti, G. (1994). Evidence for a possible neuroanatomical basis for lexical processing of nouns and verbs. *Neuropsychologia*, *32*(11), 1325–1341.
- De Clercq, P., Kries, J., Mehraram, R., Vanthornhout, J., Francart, T., & Vandermosten, M. (2022). Decreased neural envelope tracking in individuals with post-stroke aphasia. In *Poster presented at neuroscience 2022 (society for neuroscience annual meeting)*, november 12–16.
- Degano, G., Donhauser, P., Gwilliams, L., Merlo, P., & Golestani, N. (2022). Cortical signatures of the interaction between prosody and syntax during naturalistic speech listening. In *Poster presented at neuroscience 2022 (society for neuroscience annual meeting)*, november 12–16.
- Dehaene, S., Al Roumi, F., Lakretz, Y., Planton, S., & Sablé-Meyer, M. (2022). Symbols and mental programs: A hypothesis about human singularity. *Trends in Cognitive Sciences*, *26*(9), 751–766.
- Dehaene, S., Meyniel, F., Wacongne, C., Wang, L., & Pallier, C. (2015). The neural representation of sequences: From transition probabilities to algebraic patterns and linguistic trees. *Neuron*, *88*(1), 2–19.
- Dekker, R. B., Otto, F., & Summerfield, C. (2022). Curriculum learning for human compositional generalization. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(41), Article e2205582119. <https://doi.org/10.1073/pnas.2205582119>
- Dekydsprotter, L., Miller, A. K., Iverson, M., Xiong, Y., Swanson, K., & Gilbert, C. (2023). The timing versus resource problem in nonnative sentence processing: Evidence from a time-frequency analysis of anaphora resolution in successive *wh*-movement in native and nonnative speakers of French. *PLoS One*, *18*(1), Article e0275305.
- Desbordes, T., Lakretz, Y., Chanoine, V., Oquab, M., Badier, J.-M., Trébuchon, A., et al. (2023). Dimensionality and ramping: Signatures of sentence integration in the dynamics of brains and deep language models. *Journal of Neuroscience*. <https://doi.org/10.1523/JNEUROSCI.1163-22.2023>
- Dhar, M., Been, P. H., Minderaa, R. B., & Althaus, M. (2010). Reduced interhemispheric coherence in dyslexic adults. *Cortex*, *46*(6), 794–798.
- Di Liberto, G. M., Lalor, E. C., & Millman, R. E. (2018). Causal cortical dynamics of a predictive enhancement of speech intelligibility. *NeuroImage*, *166*, 247–258.
- Dijksterhuis, D. E., Self, M. W., Poesel, J. K., Peters, J. C., van Straaten, E. C. W., Idema, S., et al. (2022). Pronouns reactive concepts cells in the human medial temporal lobe. In *Poster presented at the human single neuron meeting 2022*. UCLA. November 10–11.
- Ding, N. (2022). *The neural correlates of linguistic structure building: Comments on Kazanina & Tavano*, 2022. arXiv:2212.04219.
- Ding, N., Melloni, L., Zhang, H., Tian, X., & Poeppel, D. (2016). Cortical tracking of hierarchical linguistic structures in connected speech. *Nature Neuroscience*, *19*, 158–164.
- DiNicola, L. M., & Buckner, R. L. (2021). Precision estimates of parallel distributed association networks: Evidence for domain specialization and implications for evolution and development. *Current Opinion in Behavioral Sciences*, *40*, 120–129.
- Doelling, K. B., & Assaneo, M. F. (2021). Neural oscillations are a start toward understanding brain activity rather than the end. *PLoS Biology*, *19*(5), Article e3001234.
- Donoghue, T., Cao, R., Han, C. Z., Holman, C. M., Brandmeir, N. J., Wang, S., & Jacobs, J. (2023). Single neurons in the human medial temporal lobe flexibly shift representations across spatial and memory tasks. *bioRxiv*. <https://doi.org/10.1101/2023.02.22.529437>
- Duecker, K., Gutteling, T. P., Herrmann, C. S., & Jensen, O. (2021). No evidence for entrainment: Endogenous gamma oscillations and rhythmic flicker responses coexist in visual cortex. *Journal of Neuroscience*, *41*(31), 6684–6698.
- Eisenkolb, V. M., Held, L. M., Utzschmid, A., Lin, X.-X., Krieg, S. M., Meyer, B., et al. (2022). Human acute microelectrode array recordings with broad cortical access, single-unit resolution and parallel behavioral monitoring. *bioRxiv*. <https://doi.org/10.1101/2022.10.27.514100>
- Eliasmith, C., Stewart, T. C., Choo, X., Bekolay, T., DeWolf, T., Tang, Y., & Rasmussen, D. (2012). A large-scale model of the functioning brain. *Science*, *338*(6111), 1202–1205.
- ElShafei, H. A., Zhou, Y. J., & Haegens, S. (2022). Shaping information processing: The role of oscillatory dynamics in a working memory task. *eNeuro*, *9*(5). <https://doi.org/10.1523/ENEURO.0489-21.2022>
- Esfahlani, F. Z., Jo, Y., Faskowitz, J., Byrge, L., Kennedy, D. P., Sporns, O., & Betzel, R. F. (2020). High-amplitude cofluctuations in cortical activity drive functional connectivity. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(45), 28393–28401.

- Everaert, M. B. H., Huybregts, M. A. C., Chomsky, N., Berwick, R. C., & Bolhuis, J. J. (2015). Structures, not strings: Linguistics as part of the cognitive sciences. *Trends in Cognitive Sciences*, 19(12), 729–743.
- Fellner, M.-C., Gollwitzer, S., Rampp, S., Kreiselmeyr, G., Bush, D., Diehl, B., Axmacher, N., Hamer, H., & Hanslmayr, S. (2019). Spectral fingerprints or spectral tilt? Evidence for distinct oscillatory signatures of memory formation. *PLoS Biology*, 17, Article e3000403.
- Ferguson, K. A., & Cardin, J. A. (2020). Mechanisms underlying gain modulation in the cortex. *Nature Neuroscience*, 21, 80–92.
- Fernández-Ruiz, A., Oliva, A., Fermino de Oliveira, E., Rocha-Almeida, F., Tingley, D., & Buzsáki, G. (2019). Long-duration hippocampal sharp wave ripples improve memory. *Science*, 364(6445), 1082–1086.
- Fernández-Ruiz, A., Sirota, A., Lopes-dos-Santos, V., & Dupret, D. (2023). Over and above frequency: Gamma oscillations as units of neural circuit operations. *Neuron*, 111(7), 936–953.
- Fitch, W. T. (2021). Information and the single cell. *Current Opinion in Neurobiology*, 71, 150–157.
- Forseth, K. J., Hickok, G., Rollo, P. S., & Tandon, N. (2020). Language prediction mechanisms in human auditory cortex. *Nature Communications*, 11, 5240.
- Frankland, S. M., & Greene, J. D. (2015). An architecture for encoding sentence meaning in left mid-superior temporal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, 112, 11732–11737.
- Freeman, W. J. (1975). *Mass action in the nervous system: Examination of the neurophysiological basis of adaptive behavior through the EEG*. New York: Academic Press.
- Fridriksson, J., Fillmore, P., Guo, D., & Rorden, C. (2015). Chronic Broca's aphasia is caused by damage to Broca's and Wernicke's areas. *Cerebral Cortex*, 25(12), 4689–4696.
- Fried, I. (2022). Neurons as will and representation. *Nature Reviews Neuroscience*, 23(2), 104–114.
- Friederici, A. D. (2017). *Language in our brain: The origins of a uniquely human capacity*. Cambridge, MA: MIT Press.
- Friederici, A. D. (2023). Evolutionary neuroanatomical expansion of Broca's region serving a human-specific function. *Trends in Neurosciences*. <https://doi.org/10.1016/j.tins.2023.07.004>
- Friederici, A. D., & Singer, W. (2015). Grounding language processing on basic neurophysiological principles. *Trends in Cognitive Sciences*, 19(6), 329–338.
- Fries, P. (2009). Neuronal gamma-band synchronization as a fundamental process in cortical computation. *Annual Review of Neuroscience*, 32, 209–224.
- Fries, P. (2015). Rhythms for cognition: Communication through coherence. *Neuron*, 88(1), 220–235.
- Friese, U., Koster, M., Hassler, U., Martens, U., Trujillo-Barreto, N., & Gruber, T. (2013). Successful memory encoding is associated with increased cross-frequency coupling between frontal theta and posterior gamma oscillations in human scalp-recorded EEG. *NeuroImage*, 66, 642–647. <https://doi.org/10.1016/j.neuroimage.2012.11.002>
- Frisby, S. L., Halai, A. D., Cox, C. R., & Lambon Ralph, M. A. (2023). Decoding semantic representations in mind and brain. *Trends in Cognitive Sciences*. <https://doi.org/10.1016/j.tics.2022.12.006>
- Fröhlich, F. (2015). Experiments and models of cortical oscillations as a target for noninvasive brain stimulation. *Progress in Brain Research*, 222, 41–73.
- Fromont, L. A., Steinhauer, K., & Royle, P. (2020). Verbing nouns and nouning verbs: Using a balanced design provides ERP evidence against “syntax-first” approaches to sentence processing. *PLoS One*, 15(3), Article e0229169.
- Gagol, A., Magnuski, M., Kroczyk, B., Kalamala, P., Ociepa, M., Santarnecchi, E., et al. (2018). Delta-gamma coupling as a potential neurophysiological mechanism of fluid intelligence. *Intelligence*, 66, 54–63.
- Gaito, J. (1976). Molecular psychobiology of memory: Its appearance, contributions, and decline. *Physiological Psychology*, 4, 476–484.
- Gallistel, C. R. (2017). The coding question. *Trends in Cognitive Sciences*, 21(7), 498–508.
- Gallistel, C. R. (2021). The physical basis of memory. *Cognition*, 213, Article 104533.
- Galuske, R. A. W., Munk, M. H. J., & Singer, W. (2019). Relation between gamma oscillations and neuronal plasticity in the visual cortex. *Proceedings of the National Academy of Sciences of the United States of America*, 116(46), 23317–23325.
- Gehrig, J., Michalareas, G., Forster, M.-T., Lei, J., Hok, P., Laufs, H., et al. (2019). Low frequency oscillations code speech during verbal working memory. *Journal of Neuroscience*, 39(33), 6498–6512.
- Gershman, S. J. (2023). The molecular memory code and synaptic plasticity: A synthesis. *Biosystems*, 224, Article 104825.
- Glushko, A., Poeppel, D., & Steinhauer, K. (2022). Overt and implicit prosody contribute to neurophysiological responses previously attributed to grammatical processing. *Scientific Reports*, 12, Article 14759.
- Goldstein, A., Zada, Z., Buchnik, E., Schain, M., Price, A., Aubrey, B., et al. (2022). Shared computational principles for language processing in humans and deep language models. *Nature Neuroscience*, 25, 369–380.
- Gotham, M. (2016). Composing criteria of individuation in copredication. *Journal of Semantics*, 34(2), 333–371.
- Goucha, T., Zaccarella, E., & Friederici, A. D. (2017). A revival of Homo loquens as a builder of labeled structures: Neurocognitive considerations. *Neuroscience & Biobehavioral Reviews*, 81(B), 213–224.
- Graves, W. W., Purcell, J., Rothlein, D., Bolger, D. J., Rosenberg-Lee, M., & Staples, R. (2022). Correspondence between cognitive and neural representations for phonology, orthography, and semantics in supramarginal compared to angular gyrus. *Brain Structure and Function*. <https://doi.org/10.1007/s00429-022-02590-y>
- Gross, J., Hoogenboom, N., Thut, G., Schyns, P., Panzeri, S., Belin, P., & Garrod, S. (2013). Speech rhythms and multiplexed oscillatory sensory coding in the human brain. *PLoS One*, 11(12), Article e1001752.
- Gwilliams, L. (2020). How the brain composes morphemes into meaning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 375(1791), Article 20190311.
- Hagoort, P. (2005). On Broca, brain, and binding: A new framework. *Trends in Cognitive Sciences*, 9, 416–423.
- Hagoort, P. (2013). MUC (memory, unification, control) and beyond. *Frontiers in Psychology*, 4, 416.
- Hagoort, P. (2023). The language marker hypothesis. *Cognition*, 230, Article 105252.
- Hale, J. T., Campanelli, L., Li, J., Bhattasali, S., Pallier, C., & Brennan, J. R. (2022). Neurocomputational models of language processing. *Annual Review of Linguistics*, 8, 427–446.
- Halgren, M., Fabo, D., Ulbert, I., Madsen, J. R., Eröss, L., Doyle, W. K., Devinsky, O., Schomer, D., Cash, S. S., & Halgren, E. (2017). Superficial slow rhythms integrate cortical processing in humans. *Scientific Reports*, 8, 2055.
- Hanslmayr, S., Jensen, O., & Staresina, B. (2021). In M. Kahana, & A. Wagner (Eds.), *Oxford handbook of human memory: Oscillatory brain mechanisms for memory formation – online and offline processes*. Oxford: Oxford University Press.
- Harris, A. M. (2023). Phase resets undermine measures of phase-dependent perception. *Trends in Cognitive Sciences*. <https://doi.org/10.1016/j.tics.2022.12.008>
- Hasson, U., Egidi, G., Marelli, M., & Willems, R. M. (2018). Grounding the neurobiology of language in first principles: The necessity of non-language-centric explanations for language comprehension. *Cognition*, 180, 135–157.
- Hauser, M., & Watumull, J. (2017). The universal generative faculty: The source of our expressive power in language, mathematics, morality, and music. *Journal of Neurolinguistics*, 43(B), 78–94.
- Hermiller, M. S., Chen, Y. F., Parrish, T. B., & Voss, J. L. (2020). Evidence for immediate enhancement of hippocampal memory encoding by network-targeted theta-burst stimulation during concurrent fMRI. *Journal of Neuroscience*, 40(37), 7155–7168.
- Heusser, A. C., Poeppel, D., Ezzyat, Y., & Davachi, L. (2016). Episodic sequence memory is supported by a theta-gamma phase code. *Nature Neuroscience*, 19(10), 1374–1380.
- Honari-Jahromi, M., Chouinard, B., Blanco-Elorrieta, E., Pylkkänen, L., & Fyshe, A. (2021). Neural representation of words within phrases: Temporal evolution of color-adjectives and object-nouns during simple composition. *PLoS One*, 16(3), Article e0242754.
- Hunter, T. (2019). Left-corner parsing of minimalist grammars. In R. C. Berwick, & E. P. Stabler (Eds.), *Minimalist parsing* (pp. 125–158). Oxford: Oxford University Press.
- Hu, J., Small, H., Kean, H., Takahashi, A., Zekelman, L., Kleinman, D., et al. (2022). Precision fMRI reveals that the language-selective network supports both phrase-structure building and lexical access during language production. *Cerebral Cortex* *hvac*, 350.

- Jansen, M., Li, X., Lashgari, R., Kremkow, J., Bereshpolova, Y., Swadlow, H. A., et al. (2015). Chromatic and achromatic spatial resolution of local field potentials in awake cortex. *Cerebral Cortex*, 25, 3877–3893.
- Jensen, O., Gips, B., Bergmann, T. O., & Bonnefond, M. (2014). Temporal coding organized by coupled alpha and gamma oscillations prioritize visual processing. *Trends in Neurosciences*, 37(7), 357–369.
- Jin, P., Lu, Y., & Ding, N. (2020). Low-frequency neural activity reflects rule-based chunking during speech listening. *Elife*, 9, Article e55613.
- Johari, K., Riccardi, N., & Desai, R. H. (2023). Temporal features of concepts are grounded in time perception neural networks: An EEG study. *Brain and Language*, 237, Article 105220.
- Johnson, E. L., King-Stephens, D., Weber, P. B., Laxer, K. D., Lin, J. J., & Knight, R. T. (2018). Spectral imprints of working memory for everyday associations in the frontoparietal network. *Frontiers in Systems Neuroscience*, 12, 65.
- Johnson, E. L., Lin, J. J., King-Stephens, D., Weber, P. B., Laxer, K. D., Saez, I., et al. (2023). A rapid theta network mechanism for flexible information encoding. *Nature Communications*, 14, 2872.
- Joyce, J. (2012). In R.-J. Henkes, E. Bindervoet, & F. Fordham (Eds.), *Finnegans wake*. Oxford: Oxford University Press.
- Junker, F. B., Schlawfke, L., Lange, J., & Schmidt-Wilcke, T. (2023). The angular gyrus serves as an interface between the non-lexical reading network and the semantic system: Evidence from dynamic causal modeling. *Brain Structure and Function*. <https://doi.org/10.1007/s00429-023-02624-z>
- Kastellakis, G., Silva, A. J., & Piorazi, P. (2016). Linking memories across time via neuronal and dendritic overlaps in model neurons with active dendrites. *Cell Reports*, 17, 1491–1504.
- Kaufeld, G., Bosker, H. R., Ten Oever, S., Alday, P. M., Meyer, A. S., & Martin, A. E. (2020). Linguistic structure and meaning organize neural oscillations into a content-specific hierarchy. *Journal of Neuroscience*, 40(49), 9467–9475.
- Kaushik, K., & Martin, A. E. (2022). A mathematical neural process model of language comprehension, from syllable to sentence. *PsyArXiv*. <https://doi.org/10.31234/osf.io/xs5kr>
- Kay, L. M., & Lazzara, P. (2010). How global are olfactory bulb oscillations? *Journal of Neurophysiology*, 104(3), 1768–1773.
- Kazanina, N., & Tavano, A. (2023a). What neural oscillations can and cannot do for syntactic structure building. *Nature Reviews Neuroscience*, 24, 113–128.
- Kazanina, N., & Tavano, A. (2023b). Reply to ‘Low-frequency neural parsing of hierarchical linguistic structures’. *Nature Reviews Neuroscience*. <https://doi.org/10.1038/s41583-023-00750-5>
- Kazanina, N., & Tavano, A. (2023c). Reply to ‘What oscillations can do for syntax depends on your theory of structure building’. *Nature Reviews Neuroscience*. <https://doi.org/10.1038/s41583-023-00735-4>
- Keitel, A., Gross, J., & Kayser, C. (2018). Perceptually relevant speech tracking in auditory and motor cortex reflects distinct linguistic features. *PLoS Biology*, 16(3), Article e2004473.
- Keitel, A., Ince, R. A. A., Gross, J., & Kayser, C. (2017). Auditory cortical delta-entrainment interacts with oscillatory power in multiple fronto-parietal networks. *NeuroImage*, 147, 32–42.
- Keshishian, M., Akkol, S., Herrero, J., Bickel, S., Mehta, A. D., & Mesgarani, N. (2023). Joint, distributed and hierarchically organized encoding of linguistic features in the human auditory cortex. *Nature Human Behaviour*. <https://doi.org/10.1038/s41562-023-01520-0>
- Khandhadia, A. P., Murphy, A. P., Koyano, K. W., & Leopold, D. A. (2023). Encoding of 3D physical dimensions by face-selective cortical neurons. *Proceedings of the National Academy of Sciences of the United States of America*, 120(9), Article e2214996120.
- Kleiner, J., & Hoel, E. (2021). Falsification and consciousness. *Neuroscience of Consciousness*, 1, niab001.
- Klimovich-Gray, A., Barrena, A., Agirre, E., & Molinaro, N. (2021). One way or another: Cortical language areas flexibly adapt processing strategies to perceptual and contextual properties of speech. *Cerebral Cortex*, 31(9), 4092–4103.
- Kocsis, Z., Jenison, R. L., Taylor, P. N., Calmus, R. M., McMurray, B., Rhone, A. E., Sarrett, M. E., Streese, C. D., Kikuchi, Y., Gander, P. E., et al. (2023). Immediate neural impact and incomplete compensation after semantic hub disconnection. *Nature Communications*, 14, 6264.
- Kopell, N., Ermentrout, G. B., Whittington, M. A., & Traub, R. D. (2000). Gamma rhythms and beta rhythms have different synchronization properties. *Proceedings of the National Academy of Sciences of the United States of America*, 97(4), 1867–1872.
- Kozlov, M. (2023). ‘Disruptive’ science has declined – and no one knows why. *Nature News*, 4. <https://doi.org/10.1038/d41586-022-04577-5>. January.
- Krakauer, J. W. (2022). Modular brain, entangled argument. *Journal of Cognitive Neuroscience*. https://doi.org/10.1162/jocn_a_01932
- Krauskop, A., & Lau, E. (2022). Moving away from lexicalism in psycho- and neuro-linguistics. *PsyArXiv*. <https://doi.org/10.31234/osf.io/vyf94>
- Krohn, S., Schwannenflug, N. V., Waschke, L., Romanello, A., Gell, M., Garrett, D. G., et al. (2023). A spatiotemporal complexity architecture of human brain activity. *Science Advances*, 9(5), Article eabq3851. <https://doi.org/10.1126/sciadv.abq3851>
- Kucewicz, M. T., Cimbalnik, J., Matsumoto, J. Y., Brinkmann, B. H., Bower, M. R., Vasoli, V., et al. (2014). High frequency oscillations are associated with cognitive processing in human recognition memory. *Brain*, 137(8), 2231–2244.
- Kuhnke, P., Beaupain, M. C., Arola, J., Kiefer, M., & Hartwigsen, G. (2022). Meta-analytic evidence for a novel hierarchical model of conceptual processing. *bioRxiv*. <https://doi.org/10.1101/2022.11.05.515278>
- Kujala, J., Mäkelä, S., Ojala, P., Hyönä, J., & Salmelin, R. (2023). Beta- and gamma-band oscillatory connectivity support naturalistic reading of continuous text. *bioRxiv*. <https://doi.org/10.1101/2023.08.21.554068>
- Kujala, T., Partanen, E., Virtala, P., & Winkler, I. (2023). Prerequisites of language acquisition in the newborn brain. *Trends in Neurosciences*. <https://doi.org/10.1016/j.tins.2023.05.011>
- Kullmann, D. M. (2020). *Editorial Brain*, 143(4), 1045.
- Kurth-Nelson, Z., Behrens, T., Wayne, G., Miller, K., Luettgau, L., Dolan, R., et al. (2023). Replay and compositional computation. *Neuron*, 111. <https://doi.org/10.1016/j.neuron.2022.12.028>
- Laland, K., & Seed, A. (2021). Understanding human cognitive uniqueness. *Annual Review of Psychology*, 72, 689–716.
- Lambon Ralph, M. A., Jefferies, E., Patterson, K., & Rogers, T. T. (2017). The neural and computational bases of semantic cognition. *Nature Reviews Neuroscience*, 18, 42–55.
- Lam, N. H. L., Schoffelen, J.-M., Uddén, J., Hultén, A., & Hagoort, P. (2016). Neural activity during sentence processing as reflected in theta, alpha, beta, and gamma oscillations. *NeuroImage*, 142, 43–54.
- Lasnik, H. (2017). The locality of transformational movement: Progress and prospects. In J. McGilvray (Ed.), *The Cambridge companion to Chomsky* (pp. 39–60). Cambridge: Cambridge University Press.
- Laumann, T. O., & Snyder, A. Z. (2021). Brain activity is not only for thinking. *Current Opinion in Behavioral Sciences*, 40, 130–136.
- Leckey, M., Troyer, M., & Federmeier, K. D. (2023). Patterns of hemispheric asymmetry provide evidence dissociating the semantic and syntactic P600. *Neuropsychologia*, 179, Article 108441.
- Legua, B. C., Jacobs, J., & Kahana, M. (2012). Human hippocampal theta oscillations and the formation of episodic memories. *Hippocampus*, 22(4), 748–761. <https://doi.org/10.1002/hipo.20937>
- Lei, V. L. C., Leong, T. I., Leong, C. T., Liu, L., Choi, C. U., Sereno, M. I., Li, D., & Huang, R.-S. (2023). Phase-encoded fMRI tracks down brainstorms of natural language processing with sub-second precision. *bioRxiv*. <https://doi.org/10.1101/2023.05.29.542546>
- Leivada, E. (2017). What’s in (a) label? Neural origins and behavioral manifestations of identity avoidance in language and cognition. *Biolinguistics*, 11, 221–250.
- Leonard, M., Gwilliams, L., Sellers, K., Chung, J., Datta, B., & Chang, E. (2022). Single neuron encoding of speech across cortical layers of the human superior temporal gyrus. In *Presentation at the society for the neurobiology of language annual meeting. October 6–8*.
- Łeśki, S., Lindén, H., Tetzlaff, T., Pettersen, K. H., & Einevoll, G. T. (2013). Frequency dependence of signal power and spatial reach of the local field potential. *PLoS Computational Biology*, 9(7), Article e1003137.
- Leszczynski, M., Barczak, A., Kajikawa, Y., Ulbert, I., Falchier, A. Y., Tal, I., et al. (2020). Dissociation of broadband high-frequency activity and neuronal firing in the neocortex. *Science Advances*, 6(33), Article eabb0977. <https://doi.org/10.1126/sciadv.abb0977>
- Lewis, S., & Phillips, C. (2015). Aligning grammatical theories and language processing models. *Journal of Psycholinguistic Research*, 44, 27–46.

- Lewis, S., Schoffelen, J.-M., Bastiaansen, M., & Schriefers, H. (2023). Is beta in agreement with the relatives? Using relative clause sentences to investigate MEG beta power dynamics during sentence comprehension. *Psychophysiology*. <https://doi.org/10.1111/psyp.14332>
- Liao, D. A., Brecht, K. F., Johnston, M., & Nieder, A. (2022). Recursive sequence generation in crows. *Science Advances*, 8(44). <https://doi.org/10.1126/sciadv.abq3356>
- Li, J., & Hale, J. T. (2019). In E. P. Stabler, & R. C. Berwick (Eds.), *Grammatical predictors for fMRI timecourses. Minimalist Parsing* (pp. 159–173). Oxford: Oxford University Press.
- Lisman, J., Cooper, K., Sehgal, M., & Silva, A. J. (2018). Memory formation depends on both synapse-specific modifications of synaptic strength and cell-specific increases in excitability. *Nature Neuroscience*, 21, 309–314.
- Lisman, J. E., & Jensen, O. (2013). The theta-gamma neural code. *Neuron*, 77, 1002–1016.
- Liu, Y., Dolan, R. J., Kurth-Nelson, Z., & Behrens, T. E. J. (2019). Human replay spontaneously reorganizes experience. *Cell*, 178, 640–652. e14.
- Liu, Y., Gao, C., Wang, P., Friederici, A. D., Zaccarella, E., & Chen, L. (2023). Exploring the neurobiology of merge at a basic level: Insights from a novel artificial grammar paradigm. *Frontiers in Psychology*, 14, Article 1151518.
- Liu, Y.-F., Rapp, B., & Bedny, M. (2023). Reading braille by touch recruits posterior parietal cortex. *Journal of Cognitive Neuroscience*, 35(10), 1593–1616.
- Lizarazu, M., Carreiras, M., & Molinaro, N. (2023). Theta-gamma phase-amplitude coupling in auditory cortex is modulated by language proficiency. *Human Brain Mapping*. <https://doi.org/10.1002/hbm.26250>
- Long, M. A., Jin, D. Z., & Fee, M. S. (2010). Support for a synaptic chain model of neuronal sequence generation. *Nature*, 468, 394–399.
- Lopopolo, A., van den Bosch, A., Petersson, K.-M., & Willems, R. M. (2021). Distinguishing syntactic operations in the brain: Dependency and phrase-structure parsing. *Neurobiology of Language*, 2(1), 152–175.
- Lowder, M. W., Cardoso, A., Pittman, M., & Zhou, A. (2022). *Effects of syntactic structure on the processing of lexical repetition during sentence reading*. Memory & Cognition. <https://doi.org/10.3758/s13421-022-01380-5>
- Lu, Y., Jin, P., Pan, X., & Ding, N. (2022a). Delta-band neural activity primarily tracks sentences instead of semantic properties of words. *NeuroImage*, 251, Article 118979.
- Lu, Y., Jin, P., Pan, X., & Ding, N. (2022b). Delta-band neural tracking primarily reflects rule-based chunking instead of semantic relatedness between words. *Cerebral Cortex bhac*, 354.
- Lundqvist, M., Brincat, S. L., Rose, J., Warden, M. R., Buschman, T., Miller, E. K., & Herman, P. (2023). Working memory control dynamics follow principles of spatial computing. *Nature Communications*, 14, 1429.
- Lundqvist, M., Herman, P., Warden, M. R., Brincat, S. L., & Miller, E. K. (2018). Gamma and beta bursts during working memory readout suggest roles in its volitional control. *Nature Communications*, 9, 394.
- Makuuchi, M., & Friederici, A. D. (2013). Hierarchical functional connectivity between the core language system and the working memory system. *Cortex*, 49, 2416–2423.
- Malik-Moraleda, M., Ayyash, D., Gallée, J., Affourtit, J., Hoffmann, M., Mineroff, Z., Jouravlev, O., & Fedorenko, E. (2022). An investigation across 45 languages and 12 language families reveals a universal language network. *Nature Neuroscience*, 25, 1014–1019.
- Malik-Moraleda, M., Jouravlev, O., Mineroff, Z., Cucu, T., Taliaferro, M., Mahowald, K., et al. (2023). Functional characterization of the language network of polyglots and hyperpolyglots with precision fMRI. *bioRxiv*. <https://doi.org/10.1101/2023.01.19.524657>
- Marantz, A. (1997). No escape from syntax: Don't try morphological analysis in the privacy of your own lexicon. *University of Pennsylvania Working Papers in Linguistics*, 4(2), 201–225.
- Marcolli, M., Chomsky, N., & Berwick, R. C. (2023). *Mathematical structure of syntactic merge*. arXiv:2305.18278.
- Marcus, G. F. (2001). *The algebraic mind: Integrating connectionism and cognitive science*. Cambridge, MA: MIT Press.
- Marcus, G., Marblestone, A., & Dean, T. (2014). The atoms of neural computation. *Science*, 346(6209), 551–552.
- Maris, E., Fries, P., & van Ede, F. (2016). Diverse phase relations among neuronal rhythms and their potential function. *Trends in Neurosciences*, 39(2), 86–99.
- Martin, A. E. (2020). A compositional neural architecture for language. *Journal of Cognitive Neuroscience*, 32(8), 1407–1427.
- Martin, A., Holtz, A., Abels, K., Adger, D., & Culbertson, J. (2020). Experimental evidence for the influence of structure and meaning on linear order in the noun phrase. *Glossa: A Journal of General Linguistics*, 5(1), 97.
- Martorell, J. (2021). Review of elliot murphy, the oscillatory nature of language. *Journal of Linguistics*, 57(2), 453–457.
- Martorell, J., Morucci, P., Mancini, S., & Molinaro, N. (2023). Sentence processing: How words generate syntactic structures in the brain. In M. Grimaldi, E. Brattico, & Y. Shtyrov (Eds.), *Language electrified: Principles, methods, and future Perspectives of investigation. Neuromethods 202* (pp. 551–579). New York: Humana Press.
- Matar, S., Dirani, J., Marantz, A., & Pyllkänen, L. (2021). Left posterior temporal cortex is sensitive to syntax within conceptually matched Arabic expressions. *Scientific Reports*, 11, 7181.
- Matchin, W. (2023). Lexico-semantics obscures lexical syntax. *Frontiers in Language Sciences*, 2, Article 1217837.
- Matchin, W., Basilakos, A., den Ouden, D.-B., Stark, B. C., Hickok, G., & Fridriksson, J. (2022). Functional differentiation in the language network revealed by lesion-symptom mapping. *NeuroImage*, 247, Article 118778.
- Matchin, W., Basilakos, A., Stark, B. C., den Ouden, D.-B., Fridriksson, J., & Hickok, G. (2020). Agrammatism and paragrammatism: A cortical double dissociation revealed by lesion-symptom mapping. *Neurobiology of Language*, 1(2), 208–225.
- Matchin, W., den Ouden, D.-B., Basilakos, A., Stark, B. C., Fridriksson, J., & Hickok, G. (2023). Grammatical parallelism in aphasia: A lesion-symptom mapping study. *Neurobiology of Language*. https://doi.org/10.1162/nol_a_00117
- Matchin, W., den Ouden, D.-B., Hickok, G., Hillis, A. E., Bonilha, L., & Fridriksson, J. (2022). The Wernicke conundrum revisited: Evidence from connectome-based lesion-symptom mapping. *Brain*, 145(11), 3916–3930.
- McCarty, M. J., Woolnough, O., Mosher, J. C., Seymour, J., & Tandon, N. (2022). The listening zone of human electrographic field potential recordings. *eNeuro*, 9(2). ENEURO.0492-21.2022.
- McLelland, D., & VanRullen, R. (2016). Theta-gamma coding meets communication-through-coherence: Neuronal oscillatory multiplexing theories reconciled. *PLoS Computational Biology*, 12(10), Article e1005162.
- Mendoza-Halliday, D., Major, A. J., Lee, N., Lichtenfeld, M., Carlson, B., Mitchell, B., et al. (2022). A ubiquitous spectrolaminar motif of local field potential power across the primate cortex. *bioRxiv*. <https://doi.org/10.1101/2022.09.30.510398>
- Mesnildrey, Q., Aksenov, A., D'Ambra, M. R., Hartwigsen, G., Volpert, V., & Beuter, A. (2023). Investigating spatiotemporal dynamics of cortical activity during language production in the healthy and lesioned brain. *bioRxiv*. <https://doi.org/10.1101/2023.04.27.538530>
- Meyer, L., Obleser, J., & Friederici, A. D. (2013). Left parietal alpha enhancement during working memory-intensive sentence processing. *Cortex*, 49(3), 711–721.
- Miller, E. K., & Wilson, M. A. (2008). All my circuits: Using multiple electrodes to understand functioning neural networks. *Neuron*, 60, 483–488.
- Mok, R. M., & Love, B. C. (2019). A non-spatial account of place and grid cells based on clustering models of concept learning. *Nature Communications*, 10, 5685. <https://doi.org/10.1038/s41467-019-13760-8>
- Mondal, P. (2022). A critical perspective on the (neuro)biological foundations of language and linguistic cognition. *Integrative Psychological and Behavioral Science*. <https://doi.org/10.1007/s12124-022-09741-0>
- Montgomery, E. D. (1886). The scientific basis of religious intuition. *Index - Feiten en Cijfers over Onze Samenleving*, ns 6. May 27.
- Mukherji, N. (2022). *The human mind through the lens of language: Generative explorations*. London: Bloomsbury.
- Muller, L., Chavane, F., Reynolds, J., & Sejnowski, T. J. (2018). Cortical travelling waves: Mechanisms and computational principles. *Nature Reviews Neuroscience*, 19(5), 255–268.
- Murphy, E. (2015a). Labels, cognomes, and cyclic computation: An ethological perspective. *Frontiers in Psychology*, 6, 715.
- Murphy, E. (2015b). The brain dynamics of linguistic computation. *Frontiers in Psychology*, 6, 1515.
- Murphy, E. (2018). Interfaces (travelling oscillations) + recursion (delta-theta code) = language. In E. Luef, & M. Manuela (Eds.), *The talking species: Perspectives on the evolutionary, neuronal and cultural foundations of language* (pp. 251–269). Graz: Unipress Graz Verlag.

- Murphy, E. (2020a). *The oscillatory nature of language*. Cambridge: Cambridge University Press.
- Murphy, E. (2020b). Language design and communicative competence: The minimalist perspective. *Glossa: A Journal of General Linguistics*, 5(1), 2.
- Murphy, E. (2020c). Commentary: A compositional neural architecture for language. *Frontiers in Psychology*, 11, 2101.
- Murphy, E., & Benítez-Burraco, A. (2018). Toward the language oscillogenome. *Frontiers in Psychology*, 9, 1999.
- Murphy, E., Forseth, K. J., Donos, C., Snyder, K. M., Rollo, P. S., & Tandon, N. (2023). The spatiotemporal dynamics of semantic integration in the human brain. *Nature Communications*, 14, 6336.
- Murphy, E., Holmes, E., & Friston, K. (2022a). *Natural language syntax complies with the free-energy principle*. arXiv:2210.15098.
- Murphy, E., Hoshi, K., & Benítez-Burraco, A. (2022b). Subcortical syntax: Reconsidering the neural dynamics of language. *Journal of Neurolinguistics*, 62, Article 101062.
- Murphy, E., Woolnough, O., Rollo, P. S., Roccaforte, Z., Segaert, K., Hagoort, P., & Tandon, N. (2022d). Minimal phrase composition revealed by intracranial recordings. *Journal of Neuroscience*, 42(15), 3216–3227.
- Nelson, M. J., El Karoui, I., Giber, K., Yang, X., Cohen, L., Koopman, H., et al. (2017). Neurophysiological dynamics of phrase-structure building during sentence processing. *Proceedings of the National Academy of Sciences of the United States of America*, 114(18), E3669–E3678.
- Nelson, M., Smith, C., Barrentine, B., Bentley, N., Basilico, D., & Walker, H. (2022). Preferential activation for semantic content words in the left anterior temporal lobe. In *Poster presented at the human single neuron meeting 2022*. UCLA. November 10–11.
- Neske, G. T., & Connors, B. W. (2016). Distinct roles of SOM and VIP interneurons during cortical up states. *Frontiers in Neural Circuits*, 10, 52.
- Nicholson, D. J., & Dupré, J. (Eds.). (2018). *Everything flows: Towards a processual philosophy of biology*. Oxford: Oxford University Press.
- Niven, J. E. (2016). Neuronal energy consumption: Biophysics, efficiency and evolution. *Current Opinion in Neurobiology*, 41, 129–135.
- Ntemou, E., Rybka, L., Lubbers, J., Tuncer, M. S., Vajkoczy, P., Rofes, P., et al. (2023). Lesion-symptom mapping of language impairments in people with brain tumours: The influence of linguistic stimuli. *Journal of Neuropsychology*. <https://doi.org/10.1111/jnp.12305>
- O'Byrne, J., & Jerbi, K. (2023). How critical is brain criticality? *Trends in Neurosciences*. <https://doi.org/10.1016/j.tins.2022.08.007>
- Oota, S. R., Gupta, M., & Toneva, M. (2022). *Joint processing of linguistic properties in brains and language models*, Article 08094. arxiv:2212.
- Pang, J. C., Aquino, K. M., Oldehinkel, M., Robinson, P. A., Fulcher, B. D., Breakspear, M., et al. (2023). Geometric constraints on human brain function. *bioRxiv*. <https://doi.org/10.1101/2022.10.04.510897>
- Park, M., Leahy, E., & Funk, R. J. (2023). Papers and patents are becoming less disruptive over time. *Nature*, 613, 138–144.
- Pefkou, M., Arnal, L. H., Fontolan, L., & Giraud, A.-L. (2017). θ -band and β -band neural activity reflect independent syllable tracking and comprehension of time-compressed speech. *Journal of Neuroscience*, 37(33), 7930–7938.
- Perge, J. A., Zhang, S., Malik, W. Q., Homer, M. L., Cash, S., Friehs, G., et al. (2014). Reliability of directional information in unsorted spikes and local field potentials recorded in human motor cortex. *Journal of Neural Engineering*, 11, Article 046007.
- Pesetsky, D. (1995). *Zero syntax*. Cambridge, MA: MIT Press.
- Pessoa, L. (2023). The entangled brain. *Journal of Cognitive Neuroscience*, 35(3), 349–360.
- Pietroski, P. (2008). Minimalist meaning, internalist interpretation. *Biolinguistics*, 2(4), 317–341.
- Pietroski, P. (2018). *Conjoining meanings: Semantics without truth values*. Oxford: Oxford University Press.
- Pinotsis, D. A., Fridman, G., & Miller, E. K. (2023). Cytoelectric coupling: Electric fields sculpt neural activity and “tune” the brain’s infrastructure. *Progress in Neurobiology*, 226, Article 102465.
- Poeppl, D., & Idsardi, W. (2022). We don’t know how the brain stores anything, let alone words. *Trends in Cognitive Sciences*, 26(12), 1054–1055.
- Prasada, S. (2021). The physical basis of conceptual representation – an addendum to Gallistel 2020. *Cognition*, 214, Article 1047516.
- Preminger, O. (2021). *Natural language without semiosis*. Presentation at the 14th annual conference on syntax, phonology and language analysis (SinForLJA 14).
- Prystauka, Y., & Lewis, A. G. (2019). The power of neural oscillations to inform sentence comprehension: A linguistic perspective. *Language and Linguistics Compass*, 13(9), Article e12347.
- Pylkkänen, L. (2019). The neural basis of combinatory syntax and semantics. *Science*, 366(6461), 62–66.
- Ramchand, G., & Svenonius, P. (2014). Deriving the functional hierarchy. *Language Sciences*, 46, 152–174.
- Rassi, E., Mendoza, G., Méndez, J. C., Merchant, H., & Haegens, S. (2023). Distinct beta frequencies reflect categorical decisions. *Nature Communications*, 14, 2923.
- Rezayat, E., Clark, K., Dehaqani, M.-R. A., & Noudoo, B. (2022). Dependence of working memory on coordinated activity across brain areas. *Frontiers in Systems Neuroscience*, 15, Article 787316.
- Riddle, J., Alexander, M. L., Schiller, C. E., Rubinow, D. R., & Frohlich, F. (2022). Reward-based decision-making engages distinct modes of cross-frequency coupling. *Cerebral Cortex*, 32(10), 2079–2094.
- Riddle, J., McFerren, A., & Frohlich, F. (2021). Causal role of cross-frequency coupling in distinct components of cognitive control. *Progress in Neurobiology*, 202, Article 102033.
- Riddle, J., Scimeca, J. M., Cellier, D., Dhanani, S., & D’Esposito, M. (2020). Causal evidence for a role of theta and alpha oscillations in the control of working memory. *Current Biology*, 30(9), 1748–1754.
- Riecke, L., Formisano, E., Sorger, B., Başkent, D., & Gaurdain, E. (2018). Neural entrainment to speech modulates speech intelligibility. *Current Biology*, 28(2), 161–169.
- Riecke, F., Warland, D., de Ruyter van Steveninck, R., & Bialek, W. (1997). *Spikes: Exploring the neural code*. Cambridge, MA: MIT Press.
- Rimmele, J. M., Sun, Y., Michalareas, G., Ghitz, O., & Poeppel, D. (2022). Dynamics of functional networks for syllable and word-level processing. *Neurobiology of Language*. https://doi.org/10.1162/nol_a_00089
- Riva, M., Wilson, S. M., Cai, R., Castellano, A., Jordan, K. M., Henry, R. G., ... Chang, E. (2022). Evaluating syntactic comprehension during awake intraoperative cortical stimulation mapping. *Journal of Neurosurgery*, 138(5), 1403–1410.
- Rust, N. C., & LeDoux, J. E. (2023). The tricky business of defining brain functions. *Trends in Neurosciences*, 46(1), 3–4.
- Ryan, T. J., Roy, D. S., Pignatelli, M., Arons, A., & Tonegawa, S. (2015). Engram cells retain memory under retrograde amnesia. *Science*, 348, 1007–1013.
- Sahin, N. T., Pinker, S., Cash, S. S., Schomer, D., & Halgren, E. (2009). Sequential processing of lexical, grammatical, and phonological information within Broca’s area. *Science*, 326, 445–449.
- Saleem, A. B., Lien, A. D., Krumin, M., Haider, B., Roman Roson, M., Ayaz, A., et al. (2017). Subcortical source and modulation of the narrowband gamma oscillation in mouse visual cortex. *Neuron*, 93, 315–322.
- Samimiazad, B., Reber, T., Borger, V., Surges, R., & Mormann, F. (2022). Single-neuron representations of ambiguous words on the human medial temporal lobe. In *Poster presented at neuroscience 2022 (society for neuroscience annual meeting)*, november 12–16.
- Sanchez-Todo, R., Bastos, A. M., Lopez-Sola, E., Mercadal, B., Santerrecchi, E., Miller, E. K., & Deco, G. (2023). A physical neural mass model framework for the analysis of oscillatory generators from laminar electrophysiological recordings. *NeuroImage*, 270, Article 119938.
- Sánchez, S. M., Schmidt, H., Gallardo, G., Anwander, A., Brauer, J., Friederici, A. D., & Knösche, T. R. (2022). White matter brain structure predicts language performance and learning success. *Human Brain Mapping*. <https://doi.org/10.1002/hbm.26132>
- Schlenker, P., Coye, C., Steinert-Threlkeld, S., Klinedinst, N., & Chemla, E. (2022). Beyond anthropocentrism in comparative cognition: Recentring animal linguistics. *Cognitive Science*, 46(12), Article e13220.
- Schmidt, F., Chen, Y.-C., Keitel, A., Rösch, S., Hannemann, R., Serman, M., et al. (2022). Neural speech tracking shifts from the syllabic to the modulation rate of speech as intelligibility decreases. *bioRxiv*. <https://doi.org/10.1101/2021.03.25.437033>
- Schneider, M., Brogini, A. C., Dann, B., Tzanou, A., Uran, C., Sheshadri, S., et al. (2021). A mechanism for inter-areal coherence through communication based on connectivity and oscillatory power. *Neuron*, 109(24), 4050–4067.
- Schneidman, E., Puchalla, J. L., Segev, R., Harris, R. A., Bialek, W., & Berry, M. J., 2nd (2011). Synergy from silence in a combinatorial neural code. *Journal of Neuroscience*, 31(44), 15732–15741. <https://doi.org/10.1523/JNEUROSCI.0301-09.2011>

- Sherman, M. A., Lee, S., Law, R., Haegens, S., Thorn, C. A., Hämäläinen, M. S., et al. (2016). Neural mechanisms of transient neocortical beta rhythms: Converging evidence from humans, computational modeling, monkeys, and mice. *Proceedings of the National Academy of Sciences of the United States of America*, 113(33), E4885–E4894.
- Slaats, S., & Martin, A. E. (2023). What's surprising about surprisal. *PsyArXiv*. <https://doi.org/10.31234/osf.io/7pvau>
- Slaats, S., Weissbart, H., Schoffelen, J.-M., Meyer, A. S., & Martin, A. E. (2023). Delta-band neural responses to individual words are modulated by sentence processing. *Journal of Neuroscience*. <https://doi.org/10.1523/JNEUROSCI.0964-22.2023>
- Smit, H. (2022). An overarching framework for understanding and explaining human nature. *Biological Theory*. <https://doi.org/10.1007/s13752-022-00425-x>
- Snyder, K. S. (2015). Sound perception: Rhythmic brain activity really is important for auditory segregation. *Current Biology*, 25, R1166–R1185.
- Snyder, K. M., Forseth, K. J., Donos, C., Rollo, P. S., Fischer-Baum, S., Breier, J., & Tandon, N. (2023). The critical role of the ventral temporal lobe in naming. *Epilepsia*. <https://doi.org/10.1111/epi.17555>
- Soroka, G. D., & Idiart, M. A. P. (2021). *Theta, alpha and gamma traveling waves in a multi-item working memory model*. arXiv:2103.15266.
- Sprouse, J., & Almeida, D. (2013). The empirical status of data in syntax: A reply to gibson and fedorenko. *Language & Cognitive Processes*, 28(3), 222–228.
- Sreekumar, V., Wittig, J. H., Chapeton, J., Inati, S. K., & Zaghoul, K. A. (2020). Low frequency traveling waves in the human cortex coordinate neural activity across spatial scales. *bioRxiv*. <https://doi.org/10.1101/2020.03.04.977173>
- Stanojević, M., Bhattasali, S., Dunagan, D., Campanelli, L., Steedman, M., Brennan, J., & Hale, J. (2021). Modeling incremental language comprehension in the brain with Combinatory Categorical Grammar. In *Proceedings of the workshop on cognitive modeling and computational linguistics* (pp. 23–38). Association for Computational Linguistics. <https://doi.org/10.18653/v1/2021.cmcl-1.3>.
- Sterling, P., & Laughlin, S. (2015). *Principles of neural design*. Cambridge, MA: MIT Press.
- Storchi, R., Bedford, R. A., Martial, F. P., Allen, A. E., Wynne, J., Montemurro, M. A., et al. (2017). Modulation of fast narrowband oscillations in the mouse retina and dLGN according to background light intensity. *Neuron*, 93, 299–307.
- Sugimoto, Y., Yoshida, R., Jeong, H., Koizumi, M., Brennan, J. R., & Oseki, Y. (2023). Localizing syntactic composition with left-corner recurrent neural network grammars. *Neurobiology of Language*. https://doi.org/10.1162/nol_a_00118
- Tavano, A., Rimmele, J. M., Michalareas, G., & Poeppel, D. (2023). Neural oscillations in EEG and MEG. In M. Grimaldi, E. Brattico, & Y. Shtyrov (Eds.), *Language electrified: Principles, methods, and future Perspectives of investigation*. *NeuroMethods* 202 (pp. 241–284). New York: Humana Press.
- Thiebaut de Schotten, M., & Forkel, S. J. (2022). The emergent properties of the connected brain. *Science*, 378(6619), 505–510.
- Thompson, G. J., Pan, W. J., Magnuson, M. E., Jaeger, D., & Keilholz, S. D. (2014). Quasi-periodic patterns (QPP): Large-scale dynamics in resting state fMRI that correlate with local infraslow electrical activity. *NeuroImage*, 84, 1018–1031.
- Toi, P. T., Jang, H. J., Min, K., Kim, S.-P., Lee, S.-K., Lee, J., Kwag, J., & Park, J.-Y. (2022). In vivo direct imaging of neuronal activity at high temporospatial resolution. *Science*, 378(6616), 160–168.
- Toneva, M., Mitchell, T. M., & Wehbe, L. (2022). Combining computational controls with natural text reveals aspects of meaning composition. *Nature Computational Science*, 2, 745–757.
- Trettenbrein, P. C. (2016). The demise of the synapse as the locus of memory: A looming paradigm shift? *Frontiers in Systems Neuroscience*, 10, 88.
- Turker, S., Kuhnke, P., Eickhoff, S. B., Caspers, S., & Hartwigsen, G. (2023). Cortical, subcortical, and cerebellar contributions to language processing: A meta-analytic review of 403 neuroimaging experiments. *Psychological Bulletin*. <https://doi.org/10.1037/bul0000403>
- Uran, C., Peter, A., Lazar, A., Barnes, W., Klön-Lipok, J., Shapcott, K. A., et al. (2021). Predictive coding of natural images by V1 activity revealed by self-supervised deep neural networks. *bioRxiv*. <https://doi.org/10.1101/2020.08.10.242958>
- Vardalaki, D., Chung, K., & Harnett, M. T. (2022). Filopodia are a structural substrate for silent synapses in adult neocortex. *Nature*, 612, 323–327.
- Verguts, T. (2017). Binding by random bursts: A computational model of cognitive control. *Journal of Cognitive Neuroscience*, 29(6), 1103–1118.
- Wang, X.-J. (2013). The prefrontal cortex as a quintessential “cognitive-type” neural circuit: Working memory and decision making. In D. T. Stuss, & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 226–248). Oxford: Oxford University Press.
- Wang, P., Knösche, T. R., Chen, L., Brauer, J., Friederici, A. D., & Maess, B. (2021). Functional brain plasticity during L1 training on complex sentences: Changes in gamma-band oscillatory activity. *Human Brain Mapping*, 42(12), 3858–3870.
- Welle, C. G., & Contreras, D. (2017). New light on gamma oscillations. *Neuron*, 93, 247–249.
- Wilson, S. M., Bautista, A., & McCarron, A. (2018). Convergence of spoken and written language processing in the superior temporal sulcus. *NeuroImage*, 171, 62–74.
- Wilson, S. M., Entrup, J. L., Schneck, S. M., Onuscheck, C. F., Levy, D. F., Rahman, M., et al. (2023). Recovery from aphasia in the first year after stroke. *Brain*, 146(3), 1021–1039.
- Woolnough, O., Donos, C., Curtis, A., Rollo, P. S., Roccaforte, Z. J., Dehaene, S., Fischer-Baum, S., & Tandon, N. (2022). A spatiotemporal map of reading aloud. *Journal of Neuroscience*, 42(27), 5438–5450.
- Woolnough, O., Donos, C., Murphy, E., Rollo, P. S., Roccaforte, Z. J., Dehaene, S., & Nitin, T. (2023). Spatiotemporally distributed frontotemporal networks for sentence reading. *Proceedings of the National Academy of Sciences of the United States of America*, 120(17), Article e2300252120.
- Woolnough, O., Donos, C., Rollo, P. S., Forseth, K. J., Yakretz, Y., Crone, N. E., et al. (2021). Spatiotemporal dynamics of orthographic and lexical processing in the ventral visual pathway. *Nature Human Behaviour*, 5, 389–398.
- Woolnough, O., Forseth, K. J., Rollo, P. S., Roccaforte, Z. J., & Tanton, N. (2022). Event-related phase synchronization propagates rapidly across human ventral visual cortex. *NeuroImage*, 256, Article 119262.
- Woolnough, O., Rollo, P. S., Forseth, K. J., Kadipasaoglu, C. M., Ekstrom, A. D., & Tandon, N. (2020). Category selectivity for face and scene recognition in human medial parietal cortex. *Current Biology*, 30(4), 2707–2715.
- Woolnough, O., Snyder, K. M., Morse, C. W., McCarty, M. J., Lhatoo, S. D., & Tandon, N. (2022c). Intraoperative localization and preservation of reading in ventral occipitotemporal cortex. *Journal of Neurosurgery*, 137(6), 1610–1617.
- Xiong, L., & Garfinkel, A. (2023). Are physiological oscillations physiological? *The Journal of Physiology*. <https://doi.org/10.1113/JP285015>
- Xu, Y., Long, X., Feng, J., & Gong, P. (2023). Interacting spiral wave patterns underlie complex brain dynamics and are related to cognitive processing. *Nature Human Behaviour*, 7, 1196–1215.
- Yang, H., Lin, Q., Han, Z., Li, H., Song, L., Chen, L., et al. (2017). Dissociable intrinsic functional networks support noun-object and verb-action processing. *Brain and Language*, 175, 29–41.
- Young, J. S., Lee, A. T., & Chang, E. F. (2021). A review of cortical and subcortical stimulation mapping for language. *Neurosurgery* *nyaa*, 436.
- Yu, X., & Lau, E. (2023). The binding problem 2.0: Beyond perceptual features. *Cognitive Science*, 47, Article e13244.
- Zabeh, E., Foley, N., Jacobs, J., & Gottlieb, J. (2022). *Traveling waves in the monkey frontoparietal network predict recent reward memory*. <https://doi.org/10.1101/2022.02.03.478583>. *bioRxiv*.
- Zarei, M., Parto Dezfouli, M., Jahed, M., & Daliri, M. R. (2020). Adaptation modulates spike-phase coupling tuning curve in the rat primary auditory cortex. *Frontiers in Systems Neuroscience*, 14, 55.
- Zhang, H., Watrous, A. J., Patel, A., & Jacobs, J. (2018). Theta and alpha oscillations are travelling waves in the human neocortex. *Neuron*, 98, 1269–1281.
- Zhang, Y., Zhang, Y., Cai, P., Luo, H., & Fang, F. (2019). The causal role of α -oscillations in feature binding. *Proceedings of the National Academy of Sciences of the United States of America*, 116(34), 17023–17028.
- Zhang, Y., Zou, J., & Ding, N. (2023). Complex mapping between neural response frequency and linguistic units in natural speech. *Journal of Cognitive Neuroscience*. https://doi.org/10.1162/jocn_a_02013

- Zielinski, M. C., Tang, W., & Jadhav, S. P. (2020). The role of replay and theta sequences in mediating hippocampal-prefrontal interactions for memory and cognition. *Hippocampus*, 30(1), 60–72.
- Zioga, I., Weissbart, H., Lewis, A. G., Haegens, S., & Martin, A. E. (2023). Naturalistic spoken language comprehension is supported by alpha and beta oscillations. *Journal of Neuroscience*, 43(20), 3718–3732.
- de Zubicaray, G. I., Arciuli, J., Kearney, E., Guenther, F., & McMahon, K. L. (2022). On the roles of form systematicity and sensorimotor effects in language processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. <https://doi.org/10.1037/xlm0001201>