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Reconceptualizing Merge in Search for the Link With Brain Oscillatory Nature of Language in Biolinguistics

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Abstract

This brief piece argues that it is desirable to reconceptualize the syntactic combinatorial mechanism Merge as a higher-order function that takes two functions (= a selector function and its 'argument' function) and yields a composite function in the context of I-language. On this functional characterization of Merge, all of the elements involved in Merge are conceived as functions as well: lexical items (LIs) as input of Merge and syntactic objects (SOs) as both input and output of Merge. It is claimed that this perspective of Merge is a bridging step toward further facilitating the mesoscopic-level (= dynome-level) investigation of the brain oscillatory nature of human language in the field of biolinguistics. In this framework, I make the case that it would be possible to analyze the brain oscillatory nature of Merge by appealing to the mathematical operation of the Fourier transform (FT) to the extent that Merge-related brain oscillations as physical waves can be captured by complex exponential functions/trigonometric functions in the temporal domain.

Keywords

I-language, Merge, brain oscillation, dynome, Fourier transform

1 Aim

With the advent of the minimalist program (Chomsky, 1995 et seq.), hierarchically structured expressions in natural language have come to be characterized as arising from potentially unbounded application of the syntactic combinatorial operation Merge (both external and internal), as formulated in (1) (see, e.g., Epstein et al., 2022 for a concise review of the historical development of (simplest) Merge in (1) and its extension to MERGE; Chomsky, 2019).[1]

(1) Merge (X, Y) = {X, Y} (where X, Y = a lexical item (LI) or a syntactic object (SO))

This brief opinion piece aims to point out that, strictly speaking, the formulation such as (1) is not ideal from the perspective of the characterization of language as I-language in generative grammar, attempting to reconceptualize Merge in search for the link with brain oscillatory nature of language in biolinguistics as proposed by Murphy (2021). It will be claimed that Merge can be formulated as being more fitting to the notion of I-language by appealing to the concept of function as an intensional entity toward the ultimate goal of approaching the biological understanding of Merge in terms of brain oscillations (see Gallistel & King, 2010 for some discussion of the use of function in the neurocomputational model of the brain).

2 I-Language and Merge

First, I would like to point out that, strictly speaking, the standard view of Merge as a label-free binary unordered set-formation operation (Chomsky, 2000 inter alia), as formulated in (1), is not consonant with the fundamental tenet of generative grammar that views language as I-language ('I-' stands for internal, individual, and intensional) (Chomsky, 1986, 1995 inter alia). Chomsky (1995, p. 15) clearly states "… *I-language*, where I is to suggest 'internal', 'individual', and 'intensional'. … It is intensional in the technical sense that the I-language is a function specified in intension, not extension: its extension is the set of SDs (what we call the *structure* of the I-language)."

Now, if the characterization of human language as I-language is on the right track, every element of I-language, including the lexicon and the Merge-generated syntactic objects (SOs), is naturally expected to be intensional as well as internal and individual, i.e., being a function of some sort. Hence, structural descriptions (SDs) in the above quote should be intensional objects.

In (1), Merge is conceived as a recursive function, an intensional entity, which takes X and Y as inputs and produces an unordered set {X, Y} as its output, which in turn can be used as input to Merge recursively. Notice, however, that the output of Merge is a set {X, Y}, which can be considered as an extensional object rather than an intensional one. Given that the set {X, Y} generated by Merge could be employed as input to Merge in a recursive fashion, it would mean that the input set-theoretic element must be regarded as extensional as well. If we strictly keep to the view of human language as I-language,

1) Although MERGE in Chomsky (2019) is defined as operating on a workspace (WS), it still virtually contains Merge as its sub-operation of syntactic combinatorial mechanism, which I am concerned with here.

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it would be more desirable to have not only Merge but also its inputs and outputs as specified in intension, i.e., functions.

3 Reconceptualizing Merge

Suppose that the above conjecture holds. Then, it means that every element that constitutes I-language is a function of some sort. Namely, X and Y as input elements and the output element SO with X and Y as its constituents are all to be functions. With this much in mind, while maintaining Chomsky's (2000) fundamental intuition that the two elements X and Y that enter into Merge are asymmetrical but departing from the extensional set-theoretic characterization of the output of Merge as in (1), I would like to put forth the following formulation of Merge in syntax, as shown in (2):

(2) Merge (X, Y) = Merge (f_x*, g_y) => $[f_x{*}(g_y)]_z$ (= w_z) (linear order irrelevant)

Merge as a higher-order function-creating function takes in X and Y as two functions, where X= f_x* and Y= g_y, and creates a new composite function $[f_x{*}(g_y)]_z$. The subscripted x in f indicates that f is a function with a variable x and the subscripted y in g indicates that g is a function with a variable y (see the explanation below for what those variables range over). In applying Merge, it is crucial to assume that the statuses of f_x and g_y are not equal/symmetrical and the two must work differently: one of them, say, f_x, is taken to serve as a function that selects for the other g_y as an element that virtually plays the role of an 'argument' for the function. The effect of * in (2) virtually corresponds to Chomsky's (2000) notion of a selector for lexical items (or SOs). Let us call the function f_x* *a selector function*. Thus, * indicates that the function f_x serves as a selector function and g_y without it indicates that it serves as an 'argument' for the selector function in a workspace (WS), creating a new complex function $[f_x{*}(g_y)]_z$ = w_z, which is to be properly interpreted at the C-I interface.

Note that the resulting function is w_z with a variable z with the same nature as the input functions and thus can naturally serve as a further input to Merge recursively. Furthermore, the mode of binary syntactic composition derives from the very nature of 'binary function composition'. On this conception of Merge, the selector function f_x* will play the role of determining the label in syntax for the newly Merge-generated syntactic object $[f_x{*}(g_y)]_z$ (= w_z) (see, e.g., Hoshi, in press for some discussion that the characteristic function will play a role of labeling in syntax, providing a principled explanation on syntactic phenomena in East Asian languages such as Japanese. Though the notation is different, the discussion in Hoshi, in press can be carried over in the following explanation).

To be more specific, what do f_x* and g_y in (2) stand for in the context of syntactic computation? Carrying over Chomsky's (2013, 2015) framework, which incorporates

Marantz's (1997) idea, with some conceptual modifications under the present framework, I will make the following theoretical claim. For the H-XP (head-complement) configuration, both the 'lexical domain' and the 'functional domain' are relevant.

In the former, the head H as a categorizer (n, v, a, p) serves as the selector function f_x^* and takes its complement XP (= a root element phrase √RP) as its 'argument' function g_y, with f_x^* determining the label of the whole SO $[f_x^*(g_y)]_z$, roughly such as nominal, verbal, adjectival, prepositional/postpositional. As for the latter, when the Merge-generated composite function $[f_x^*(g_y)]_z$ corresponds to {T, vP} or {C, TP} in the traditional notation, the functional category head T and C would be regarded as the selector function f_x^* that receives an eventuality expressed by vP as its 'argument' function g_y, yielding a tensed eventuality (= a situation) as the resultant function $[f_x^*(g_y)]_z$ in the former, and a selector function f_x^* that accepts a tensed eventuality/situation expressed by TP as its 'argument' function g_y, returning a tensed eventuality/situation with a force (e.g., interrogative/non-interrogative) (= a proposition) as the output function $[f_x^*(g_y)]_z$ in the latter, along the line of Ramchand and Svenonius (2014).

There remains a theoretical complication concerning the root element √R. In Chomsky (2013, 2015), the root element √R is assumed to be incapable of providing any label. If this is the case, the SO such as {√R, DP/nP} or {√R, vP} in the traditional notation is devoid of a label at this stage of derivation before the categorizer such as v or n is merged. On the other hand, the root element √R serves the role of a selector function f_x^* that has DP/nP or vP as its 'argument' function g_y. Given the special nature of the root element as label-free, I will tentatively assume that the root element is a special selector function that does not provide any label before its relation with a categorizer is established in the derivation, unlike other head H elements.

What about the case of {XP, YP} structures in the traditional notation such as the subject-predicate configuration {DP/nP, vP} or the configurations for {DP/nP, TP} (= subject-raising from the predicate-internal position) or {Wh-DP/nP, CP} (= the final landing-site of wh-movement)? First, for the case of {DP/nP, vP}, I will take it that vP is the selector function f_x^* that selects DP/nP as its 'argument' function g_y. Second, for the cases of {DP/nP, TP} and {Wh-DP/nP, CP}, I regard TP and CP as serving as a kind of λ-expression,[2] which is an instantiation of the selector function f_x^* that takes DP/nP and Wh-DP/nP as its 'argument' function g_y, providing the label for the whole SO $[f_x^*(g_y)]_z$. At the same time, since the wh-phrase also serves as an operator (= a function) in the operator-variable construction on the standard view, I assume that the whole SO with the initial wh-phrase as the 'argument' function g_y to the λ-expression selector function f_x^* (= CP) undergoing 'reprojection' or 'relabeling' in such a way that the wh-operator

2) See Bayırlı (2023) for detailed argumentation from a biolinguistic standpoint that lambda abstraction is a factor in human uniqueness.

will be reinterpreted as the label of the whole SO with the original CP part turning into its argument as the nuclear scope (see, e.g., Hornstein & Uriagereka, 2002; Oku, 2017).

4 Merge and Categorization

The proposed formulation of Merge in (2) has some implications not only for lexical items (LIs) and syntactic objects (SOs) as input of Merge and SOs as output of Merge but also for the domain of cognition in our species.

It is customary to posit that lexical items (LIs) in the technical sense are simplex conceptual atoms (containing bundles of features) and SOs are conceptual complexes (implicating possible rearrangement of such arrays of features) in generative grammar (Chomsky, 1995 et seq.). Note that, given (2), both simplex conceptual atoms and conceptual complexes are regarded as functions in I-language. Since I-language is only concerned with brain-internal representations (and computations), independent of entities and events in the external world, such concept-related functions indicated as f_x*, g_y, and w_z in section 3 should mediate between two brain-internal representations: one is the brain-internal representation corresponding to the 'concept/meaning' of a lexical item or an SO, i.e., λ and the other is the brain-internal representation corresponding to the 'form' of externalization of such a lexical item or an SO, i.e., π in the minimalist framework (Chomsky, 1995, et seq.).

Hoshi (2018, 2019) argues that Merge and Categorization (Cat) are two cognitive operations that enter into a productive relation in human cognition, with the former providing a means of producing an infinite array of labels for Cat in humans on top of sensorimotor domain-derived labels possibly shared with other non-human animals, leading to the enhancement of the cognitive power in our species in the sense of Tattersall (2017).

Following Hoshi (in press) and Benítez-Burraco, Hoshi, and Progovac (2023), I will assume that Cat is a brain-internal cognitive procedure like Merge, determining its membership, 'judging' whether anyone/anything can belong to a category with a certain category label. On this conception, both lexical items and SOs generated by Merge can serve as category labels. Thus, Cat is a higher-order function that 'characterizes' whether an *n* number of brain-internal representations ($n \geq 0$) corresponding to values (= tokens) of a variable of the function as possible realizations of a concept (= type) mediated by the functions f_x*, g_y, and w_z as the category labels corresponding to lexical items like *book*, *chair*, etc. or SOs like *a book*, *the chair*, *a book on the desk*, *the chair is in the room*, etc. generated by Merge. As such, the variables subscripted as x, y, and z for the functions f_x*, g_y, and w_z range over neurally coded brain internal representations for the 'form' (= π in the above sense) of the I-language objects like lexical items and SOs.

Note that Cat is defined as a mental process that involves purely brain-internal representations that correspond not only to individuals but also to anything else, such as properties, events, states, and propositions. By this definition of Cat, I would like to follow Hoshi (in press) in avoiding a purely extensional characterization of a category as a set of individuals that satisfy some membership criterion related to the category label (Hoshi, 2018, 2019), which is based on the standard characteristic function that associates individuals or pairs of individuals to truth values commonly utilized in formal semantics (Dowty et al., 1981; Heim & Kratzer, 1998).

5 Some Implications for the Possible Link Between Merge and Brain Oscillatory Nature of Language

The proposed view of Merge as a higher-order function that takes functions as inputs and produces a new function as output has some biolinguistic implications. Up until recently most of the neurobiological research on language has mainly focused on what Poeppel (2012) calls the *Maps Problem*, i.e., the identification of the relevant location(s) of the neuronal network for language in the brain, employing the brain-imaging technology of electroencephalography (EEG), magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), single photon emission computed tomography (SPECT), functional near-infrared spectroscopy (fNIRS) among others (see, e.g., Friederici, 2017 for the state-of-the-art review. See also Fukui, 2017 for an attempt to map Merge in the brain). While it is true that knowing where such a neuronal network for language exists in the brain in terms of neural connectivity is of vital importance, it does not seem to be sufficient to fully understand the biological workings of language in the brain (see, e.g., Gallistel & King, 2010 for the argument that changes in synaptic conductance with the notion of an associative bond in a neuronal network are not a likely possibility for the mechanism of memory).

In the recent development of the study of brain oscillations in neuroscience, there has emerged the recognition that brain oscillations and their interactions will play a significant role in realizing various kinds of cognitive functions, language being no exception (see, e.g., Benítez-Burraco & Murphy, 2019; Benítez-Burraco, Hoshi, & Murphy, 2023; Murphy, 2021; Murphy & Benítez-Burraco, 2018; Murphy, Hoshi, et al., 2022. See also Buzsáki, 2019 for a perspective of this kind that is compatible with the I-language view of human language).[3] Based on a detailed and extensive marshaling of evidence, Murphy (2021) put forth a promising view of language as being neurally implemented

3) Brain oscillations reflect synchronized activity of ensembles of cortical or subcortical neurons in the brain and their interactions via cross-frequency coupling (CFC) (see below) will serve an important role for inter-regional efficient communication, i.e., information transmission and exchange, in the brain within the globular space of the skull (see, e.g., Buzsáki, 2006, 2010 for details).

in terms of brain oscillations and their interactions (see also Lenneberg, 1967 for a precursor to such a view).

Among a series of theses on brain oscillatory nature of language, Murphy (2021) proposes that lexical itemization is mediated by gamma oscillations (γ: ~30–150 Hz) and syntactic combinatorial operation of Merge with inputs of lexical items and SOs is implemented by cross-frequency coupling (CFC) such as the combination of phase-amplitude coupling of gamma-theta oscillations (θ: ~4–8 Hz) and theta-delta oscillations (δ: ~0.5–4 Hz). More specifically, Murphy (2021, p. 239) states that "δ waves cycle across left inferior frontal parts of the cortex, building up the syntactic workspace phrase-by-phrase and potentially being endogenously reset by a newly constructed phrase, and being coupled to traveling θ waves which perform the same function. δ would coordinate phrasal construction while θ-γ interactions would support the representational construction of linguistic feature-sets." On this conception, "the only domain-specific entities left are the representations" (Murphy, 2021, p. 245), which are assumed to be itemized by gamma-band oscillations generated across the various cortical regions (see Murphy, 2021, chapter 3 for detailed discussion on this issue).

In my opinion, the shift in generative grammar from geometrical tree diagram syntactic representations in the pre-minimalist program to set-theoretical syntactic representations in the minimalist program can be considered a desirable theoretical step toward approaching the reality of syntactic computation in the brain. However, in order to make an attempt to solve *the Mapping Problem* rather than *the Maps Problem* in Poeppel (2012), it seems to be needed to reconceptualize Merge as implicating multi-layering of intensional constructs such as functions, as I argued above, which could in principle be more naturally amenable to the analysis of syntactic computation in terms of brain oscillations along the line of Murphy (2021). In other words, I would like to propose that viewing the functions such as f_x*, g_y, and w_z in (2) as representing the mesoscopic level of dynome (Kopell et al., 2014) is instrumental in moving toward solving the Mapping Problem.

Various forms of waves in the physical world (including brain waves in the physical space of the brain) can be characterized by wave functions as a complex exponential function of roughly the form $f(x, t) = Ae^{i(kx-\omega t)}$, where A is the amplitude, e is Napier's constant, i is the imaginary number unit, k is the wave number, ω is the angular frequency, x is the location, and t is the time (see, e.g., Hirose & Longgren, 1985 for introduction to wave phenomena in general). The wave number k is generally a complex number, but if it is a real number, as when the wave is represented by a sine wave/cosine wave, $f(x, t) = A\{\cos(kx-\omega t) + i\sin(kx-\omega t)\}$.

In reality, brain waves as in other physical waves propagate spatially and oscillate temporally (Buzsáki, 2006), being subject to the wave functions mentioned above. However, to make the story simple, suppose that a certain brain oscillation related to a cognitive process such as Merge were to be recorded by, say, EEG and to be formulated in terms of a function f(t) in the temporal domain, ignoring its spatial dimension (note that the location variable x in f(x, t) is not used). In principle, whenever an EEG signal is recorded, such a brain wave can be analyzed in the frequency domain based on the mathematics of the Fourier transform (FT) (see, e.g., Stein & Shakarchi, 2003) by decomposing the complex brain wave into a combination of sine waves and cosine waves, each of which can be represented as trigonometric functions, as illustrated in (3):[4]

(3)
$$\begin{aligned} F(\omega) &= \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt \\ &= \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} f(t)\{\cos(\omega t) - i\sin(\omega t)\}dt \end{aligned}$$

Roughly, FT is a mathematical operation of integral calculus for spectral analysis in terms of a spectrum of frequencies that converts the original function (= f(t)) corresponding to a wave in the temporal domain into the frequency domain representation (= F(ω)) of the wave in question. As a result of FT, the information will be revealed as to how many waves of different frequencies (ω) are involved in the original wave expressed by the function f(t) in the temporal domain. $e^{-i\omega t}$ in the formula represents the decomposed waves in complex exponential function notation in the first line, which can be equally expressed as in the second line with the combination of cosine and sine functions due to Euler's formula. Accordingly, in theory, if we could identify a relevant brain oscillation for a cognitive process via EEG/MEG in the temporal domain, we could analyze the original brain wave by decomposing it into the component waves of different frequencies, converting from the temporal domain to the frequency domain by FT (see, e.g., Young & Eggermont, 2009).

If Murphy (2021) is on the right track in assuming that Merge is neurally implemented by cross-frequency coupling (CFC), in particular, by phase-amplitude coupling (PAC) of the phase of a slower oscillation such as θ or δ and the amplitude of a higher oscillation such as γ, then obviously FT alone does not seem to be sufficient. First, you have to analyze a certain CFC/PAC phenomenon in the brain corresponding to a certain linguistic task in order to identify a proper combination of relevant brain oscillations to account for the CFC/PAC phenomenon on the basis of a statistical method of discovering a significant interaction between two different brain oscillations with different frequencies

4) In FT, it is theoretically assumed that the distribution of various frequencies of the original wave in the temporal domain remains constant. However, in reality, such a distribution of various frequencies can change over time in the original wave, which cannot be captured in FT. In order to tackle this problem, various methods such as Discrete Fast Fourier transform and Wavelet transform are employed in analyzing oscillations in the field (see, e.g., Marks II, 2008; Walnut, 2002). I will not get into this issue here and just briefly take up FT with this limit in mind.

(see, e.g., Cohen's, 2017 generalized eigendecomposition-based cross-frequency coupling framework (gedCFC) as a new method for more precise analytical tool).

Given that CFC/PAC involves embedding an oscillation with a higher frequency into another oscillation with a lower frequency, yielding a brain oscillatory pattern implicating a modulated amplitude of the higher frequency wave by the phase of the lower frequency wave (see, e.g., Murphy, 2021 and references therein), I would like to suggest that Merge, f_x^*, g_y, and w_z in (2) could be viewed as presumably corresponding to CFC/PAC, a lower frequency oscillation, a higher frequency oscillation, and the whole modified oscillatory pattern implicating the two oscillations, respectively. Then, in theory, you could employ gedCFC and FT to analyze EEG/MEG data for obtaining the functions f_x^*, g_y, and w_z in (2) in order to obtain the frequency spectral properties of those relevant brain oscillations characterized by those functions, if the "functional characterization hypothesis of Merge" proposed in this piece is theoretically adopted.[5] While I must admit that my current proposal is still 'too simplistic' at this stage, it is hoped that it will suggest a possible direction for the investigation of the well-grounded neuro-biological implementation of Merge in the brain in the future.

What kind of a cognitive task should be instrumental in discovering the presumed relevant functions indicated by f_x^*, g_y, and w_z in (2) in my framework? While specifying the mathematical formulas for f_x^*, g_y, and w_z in concrete terms is beyond the scope of this short piece and my ability at this juncture, Suppes and Han (2000) seem to be quite suggestive. Based on EEG data and the method of discrete fast Fourier transform (FFT), they demonstrated that words such as *blue, green, red, yellow*, etc. in natural language can be represented brain-wave-wise by superposition of a few sine oscillations, as indicated in (4):

(4) $$S_i = \sum_{j=1}^{n} A_j sin\left(\omega_j t_i + \varphi_j\right)$$

Thus, a word corresponds to the superposition brain oscillation S_i for each observation i in EEG, with S_i being the sum of an n number of sine waves, where A_j, ω_j, and φ_j are the amplitude (in microvolts), frequency (in radians/s), and phase (in radians) of the jth sine wave. As such, in principle, if we could identify this kind of superposition function

5) Notice that I am NOT claiming that all the information about relevant linguistic features (morpho-phonological, syntactic, and semantic, etc.) in lexical items (LIs) and syntactic objects (SOs) generated by Merge is encoded by the functions f_x^*, g_y, and w_z. The gist of FT is that any complex brain oscillations can be decomposed into a combination of a variety of patterns of sine and cosine waves. Thus, in principle, each of the relevant linguistic features can be encoded and carried by a specific sine/cosine oscillation, which could lead to producing a virtually unlimited possibility of encoding feature-sets, given that, on top of such various patterns of combination of sine and cosine waves, parameters such as amplitude, frequency, and phase for the sine/cosine oscillation functions can assume a variety of values in a certain neuro-biologically determined range. On this view, the functions f_x^*, g_y, and w_z in (2) should be regarded as being constituted by a multitude of 'hidden' sine/cosine waves in this sense.

as candidates for the selector function f_x* and the 'argument' function g_y and if we could formulate the mathematics for CFC/PAC, we would be able to obtain the resultant function w_z.

In this connection, Murphy, Woolnough, et al.'s (2022) line of research seems to be quite promising. On the basis of fine-grained MEG (magnetoencephalography) and ECoG (electrocorticography), a type of intracranial electroencephalography (iEEG), recordings of brain oscillations from subjects for relatively simple syntactic combinatorial tasks, as exemplified by Murphy, Woolnough, et al.'s (2022) intracranial recordings of minimal phrase composition of Adjective-Noun (e.g., red car), we might be able to pin down the oscillatory properties of the noun as f_x* and the adjective as g_y and the Merged derived noun phrase as w_z in principle, if we could somehow combine the CFC/PAC detection technique and FFT as briefly discussed above.

6 Conclusion

In conclusion, this brief piece argued that it is desirable to reconceptualize the syntactic combinatorial mechanism Merge as a higher-order function that takes two functions (= a selector function and its 'argument' function) and produces a composite function. On this functional characterization of Merge, all of the elements involved in Merge are regarded as functions as well: lexical items (LIs) as input of Merge and syntactic objects (SOs) as both input and output of Merge. I claimed that this perspective of Merge is a bridging step toward further facilitating the biolinguistic mesoscopic-level investigation of the brain oscillatory nature of human language, originally launched by Murphy (2021) in the field, given that brain oscillations as physical waves can be captured by complex exponential functions/trigonometric functions in mathematical terms.

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References

Bayırlı, İ. K. (2023). Lambda abstraction as a factor in human uniqueness. *Biolinguistics, 17*, Article e11205. https://doi.org/10.5964/bioling.11205

Benítez-Burraco, A., & Murphy, E. (2019). Why brain oscillations are improving our understanding of language. *Frontiers in Behavioral Neuroscience, 13*, Article 190. https://doi.org/10.1016/j.jneuroling.2023.101139

Benítez-Burraco, A., Hoshi, K., & Murphy, E. (2023). Language deficits in GRIN2A mutations and Landau–Kleffner syndrome as neural dysrhythmias. *Journal of Neurolinguistics, 67*, Article 101139. https://doi.org/10.1016/j.jneuroling.2023.101139

Benítez-Burraco, A., Hoshi, K., & Progovac, L. (2023). The gradual coevolution of syntactic combinatorics and categorization under the effects of human self-domestication: A proposal. *Cognitive Processing, 24*, 425–439. https://doi.org/10.1007/s10339-023-01140-6

Buzsáki, G. (2006). *Rhythms of the brain.* Oxford University Press.

Buzsáki, G. (2010). Neural syntax: Cell assemblies, synapsembles, and readers. *Neuron, 68*(3), 362–385. https://doi.org/10.1016/j.neuron.2010.09.023

Buzsáki, G. (2019). *The brain from inside out.* Oxford University Press.

Chomsky, N. (1986). *Knowledge of language: Its nature, origin, and use.* Praeger.

Chomsky, N. (1995). *The minimalist program.* MIT Press.

Chomsky, N. (2000). Minimalist inquiries: The framework. In R. Martin, D. Michaels, & J. Uriagereka (Eds.), *Step by step: Essays on minimalist syntax in honor of Howard Lasnik* (pp. 89–155). MIT Press.

Chomsky, N. (2013). Problems of projection. *Lingua, 130*, 33–49. https://doi.org/10.1016/j.lingua.2012.12.003

Chomsky, N. (2015). Problems of projection: Extensions. In E. D. Domenico, C. Hamann, & S. Matteini (Eds.), *Structures, strategies and beyond: Studies in honour of Adriana Belletti* (pp. 3–16). John Benjamins.

Chomsky, N. (2019). Some puzzling foundational issues: The Reading program. *Catalan Journal of Linguistics, 2019*(Special Issue), 263–285. https://doi.org/10.5565/rev/catjl.287

Cohen, M. X. (2017). Multivariate cross-frequency coupling via generalized eigendecomposition. *eLife, 6*, Article e21792. https://doi.org/10.7554/eLife.21792

Dowty, D. R., Wall, R. E., & Peters, S. (1981). *Introduction to Montague semantics.* D. Reidel.

Epstein, S. D., Kitahara, H., & Seely, T. D. (2022). *A minimalist theory of simplest Merge.* Routledge.

Friederici, A. D. (2017). *Language in our brain: The origins of a uniquely human capacity.* MIT Press.

Fukui, N. (2017). *Merge in the mind-brain: Essays on theoretical linguistics and the neuroscience of language.* Routledge.

Gallistel, C. R., & King, A. P. (2010). *Memory and the computational brain: Why cognitive science will transform neuroscience.* Wiley-Blackwell.

Heim, I., & Kratzer, A. (1998). *Semantics in generative grammar.* Blackwell.

Hirose, A., & Longgren, K. E. (1985). *Introduction to wave phenomena.* Wiley.

Hornstein, N., & Uriagereka, J. (2002). Reprojections. In S. D. Epstein & T. D. Seely (Eds.), *Derivation and explanation in the minimalist program* (pp. 106–132). Blackwell.

Hoshi, K. (2018). Merge and labeling as descent with modification of categorization: A neo-Lennebergian approach. *Biolinguistics, 12*, 39–54. https://doi.org/10.5964/bioling.9135

Hoshi, K. (2019). More on the relations among categorization, Merge and labeling, and their nature. *Biolinguistics, 13*, 1–21. https://doi.org/10.5964/bioling.9147

Hoshi, K. (in press). The hypothesis of categorization origins of Merge and labeling in evolinguistics: Its implications to the labeling system in syntax and East Asian linguistic study. In J. Ting & Y.-Y. Hsu (Eds.), *Linguistic interfaces in East-Asian languages: A festschrift in honor of Yoshihisa Kitagawa* (pp. 61–79). Springer.

Kopell, N. J., Gritton, H. J., Whittington, M. A., & Kramer, M. A. (2014). Beyond the connectome: The dynome. *Neuron, 83*(6), 1319–1328. https://doi.org/10.1016/j.neuron.2014.08.016

Lenneberg, E. (1967). *Biological foundations of language*. Wiley.

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*, 201–225.

Marks, R. J., II. (2008). *Handbook of Fourier analysis & its applications*. Oxford University Press.

Murphy, E. (2021) *The oscillatory nature of language*. Cambridge University Press.

Murphy, E., & Benítez-Burraco, A. (2018). Toward the language oscillogenome. *Frontiers in Psychology, 9*, Article 1999. https://doi.org/10.3389/fpsyg.2018.01999

Murphy, E., Hoshi, K., & Benítez-Burraco, A. (2022). Subcortical syntax: Reconsidering the neural dynamics of language. *Journal of Neurolinguistics, 62*, Article 101062. https://doi.org/10.1016/j.jneuroling.2022.101062

Murphy, E., Woolnough, O., Rollo, P. S., Roccaforte, Z. J., Segaert, K., Hagoort, P., & Tandon, N. (2022). Minimal phrase composition revealed by intracranial recordings. *The Journal of Neuroscience, 42*(15), 3216–3227. https://doi.org/10.1523/JNEUROSCI.1575-21.2022

Oku, S. (2017). Labeling and overt/covert movements. *Nanzan Linguistics, 13*, 9–28. http://hdl.handle.net/2115/81588

Poeppel, D. (2012). The maps problem and the mapping problem: Two challenges for a cognitive neuroscience of speech and language. *Cognitive Neuropsychology, 29*(1-2), 34–55. https://doi.org/10.1080/02643294.2012.710600

Ramchand, G., & Svenonius, P. (2014). Deriving the functional hierarchy. *Language Sciences, 46*, 152–174. https://doi.org/10.1016/j.langsci.2014.06.013

Stein, E. M., & Shakarchi, R. (2003). *Fourier analysis: An introduction*. Princeton University Press.

Suppes, P., & Han, B. (2000). Brain-wave representation of words by superposition of a few sine waves. *Proceedings of the National Academy of Sciences of the United States of America, 97*(15), 8738–8743. https://doi.org/10.1073/pnas.140228397

Tattersall, I. (2017). How can we detect when language emerged? *Psychonomic Bulletin & Review, 24*, 64–67. https://doi.org/10.3758/s13423-016-1075-9

Walnut, D. F. (2002). *An introduction to wavelet analysis*. Birkhäuser.

Young, C. K., & Eggermont, J. J. (2009). Coupling of mesoscopic brain oscillations: Recent advances in analytical and theoretical perspectives. *Progress in Neurobiology, 89*(1), 61–78. https://doi.org/10.1016/j.pneurobio.2009.06.002