

The Human Oscillome and Its Explanatory Potential

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My intention in this piece is to briefly outline a novel hypothesis regarding the neurobiological implementation of feature-set binding, the labeling of feature-sets, and the resolution of linguistic dependencies arising from the cyclic combination of these labeled objects. One of the numerous motivations for this was reading Robert C. Berwick & Noam Chomsky's (B&C) recent book *Why Only Us: Language and Evolution* (Berwick & Chomsky 2016; henceforth *WOU*), which struck me as moderately comprehensive in its interdisciplinary scope (including good critical commentary on recent work in comparative neuroprimatology and theoretical biology) but severely impoverished in its range of linking hypotheses between these disciplines.

While the authors are correct to point out that the Strong Minimalist Thesis follows the 'divide-and-conquer' approach which helps narrow the gap between disciplines, their actual implementation of this approach is fairly mild and uninformative. There is lots of talk about how language is "an 'organ of the body', more or less on a par with the visual or digestive or immune system" and how it is "a subcomponent of a complex organism" (p. 56), accompanied by the usual discussion of the Newtonian dispelling of the mind-body problem—all of which is true, unequivocal, undeniable, but directionless and intensely vague. B&C discuss Lenneberg's early work on language evolution, deeming it "a model of nuanced evolutionary thinking" (p. 5), but as Lenneberg (1964: 76) himself noted, "[n]othing is gained by labeling the propensity for language as biological unless we can use this insight for new research directions—unless more specific correlates can be uncovered". The absence of concrete linking hypotheses between the domains of the life, cognitive, and biological sciences in *WOU*, and its concern with isolated and disparate sources of evidence which lend support to an emergentist model of language evolution, whatever its merits, does not promote this kind of cross-disciplinary collaboration. I think that from the perspective of brain dynamics, what the authors call the "Basic Property" (Merge) can be explored in a number of interesting and fruitful ways, promoting further interdisciplinary work and relying on a neurolinguistic perspective which, unlike *WOU*, goes beyond the cortex and examines the important role of subcortical structures like the thalamus and basal ganglia.

To set the scene for what follows, it is useful to consider the framework in Boeckx & Theofanopolou (2015), which highlights the inadequacy of standard

This work was supported by an Economic and Social Research Council scholarship (1474910). My thanks go to Kleantes Grohmann for his careful editorial assistance and to David Adger for helpful comments.



cladistic thinking so prevalent in much of contemporary biolinguistics (most notably in the FLN–FLB distinction, under which the ‘Basic Property’ was simply added ‘on top’ of faculties shared with other species, as if no reciprocal causation had occurred). Boeckx & Theofanopoulou “very much doubt that cognition can be studied independently of the basic neurophysiological principles that produce it”, going against the many ‘Marr Misreaders’, as I term them in Murphy (forthcoming), who claim that the three Marrian levels need to be studied in a segregated fashion, privileging the computational level.¹ For instance, while computationally distinct, music and language share a number of important algorithmic properties such as prediction, synchronization, turn-taking, and oscillatory entrainment (Doelling & Poeppel 2015). This seems to emerge from cell assembly specializations and distinct rhythmic profiles; language and music have different hierarchical processing networks but shared working memory and cognitive control systems (Rogalsky et al. 2011).

Much work in contemporary neurolinguistics appears instead to be effectively crypto-creationist in its monolithic approach to language implementation and evolution, discussing it in terms of ‘syntax’, ‘phonology’, and other complex categories—similar to an ophthalmologist speculating about the evolution of ‘red’ and ‘green’. Top-down perspectives, of the kind proposed in *WOU*, are useful up until the point that sufficiently decomposed and generic sub-operations and processes have been discovered. But insisting on a top-down perspective ‘all the way down’ is inconsistent with both Darwinian and Thompsonian thinking. Indeed, the importance of domestication and cultural evolution for language is also often overlooked, despite it being known that domestication can directly impact computational competence and trigger previously dormant operations (Okanoya 2012; Murphy 2015a).

The lexicalist framework of *WOU*, and much recent work in linguistics (see Boeckx 2014 and Murphy 2015c for critiques), presents a number of obstacles for evolutionary theses. Most notably, contemporary neurobiology is far from achieving an understanding of *representations*, and I think focus should instead be placed on investigating *operations*, with set-formation and labeling (a composite of object permanence and property attribution) having a much greater potential to be grounded in (oscillatory) processes than roots and intransitive verbs. Studies of particular oscillations are increasingly being linked to gene sets via their neurochemical implementation, and if cognitive capacities like language can be causally derived from oscillatory factors then this would serve as an important step in narrowing the bridge between cognition and neurobiology.

¹ It’s possible to detect a peculiar kind of dualism in the work of Marr Misreaders. To take one of numerous examples, Gazzaniga (1995: xiii) argues that algorithms “drive structural neural elements into physiological activity”, suggesting that higher-order entities have causal force over neural assemblies. Moreover, in conceptual terms computational investigations boil down to input–output schemas, by definition insufficient to understand the biological basis of language, despite the common generativist claim that theoretical syntax amounts to biology “at a higher level of abstraction”, whatever that means. This argument has always felt to me like a totally needy cop-out, similar to someone ditching their A Level physics class and, when challenged by their teacher about their absence, replying: “But I’ve chosen to write some poetry about gravity while jumping and rolling down the hill in the park, because I thought that was a good way of studying physics at a higher level of abstraction.”

The neurolinguistic approach in *WOU* relies on outdated assumptions, sticking purely to localization issues and answering the ‘How’ question of language evolution by just pointing to good old BA44 and 45. “Our general problem”, B&C write, “is that we understand very little about how even the most basic computational operations might be carried out in the neural ‘wetware’” (p. 50); however, a number of recent proposals have attempted to establish intriguing relations between brain function and language comprehension (Lewis et al. 2015; Lewis & Bastiaansen 2015, among many others). These considerations embrace how the brain actually operates (via oscillations and their various coupling operations). B&C additionally “(speculatively) posit that the word-like elements, or at least their features as used by Merge, are somehow stored in the middle temporal cortex as the ‘lexicon’” (p. 159). This ignores well-accepted findings that conceptual representations are widely distributed across several regions, even if the middle temporal cortex acts as a store for many core representations and a crucial memory buffer in phrase structure building (just as how Broca’s area is most likely a similar kind of buffer in syntactic computation, and not the “seat of syntax” as Angela Friederici has often claimed; see Blank et al. 2016 for evidence of distributed syntactic processing).

B&C’s middle temporal cortex hypothesis relies solely on imaging studies which point to regional specialization for particular language tasks, but this methodological cut-off point, while typically acknowledged by fMRI experimentalists (who can now achieve voxels of 0.8mm^3), is side-stepped by B&C, who ignore the important language-related activation in non-specialized voxels. No-one would claim that the responses to tactile sensation in non-selective regions are somehow not part of the story of how we become acquainted with surfaces, and so a laser-like focus on middle temporal cortex amounts to a severely run-down neurolinguistic model. When limited to such a narrow view of functional (not to mention dynamic) brain activity, it is almost inevitable that one would be forced to arrive at bizarre and outmoded models of language localization.

It is widely assumed that human and animal concepts are composed of necessary and sufficient features surrounded by a periphery of ancillary but related features used to ‘point’ the comprehender in the right conceptual direction (grey feathers may be suggestive of a bird, for instance, but are not necessarily part of one), and any neurolinguistic models informed purely by imaging studies will likely reflect only the implementational regions (and not the neurobiological mechanisms) responsible for these peripheral features. I think this point is crucial and to my knowledge has not been recognized by the neurolinguistics community.

Relatedly, localization studies impose no constraints on the theory of linguistic or cognitive structure they are putatively attempting to explore. This point is somewhat more obvious, but also seems to me unappreciated in the literature. A given brain region (say, BA45) cannot ‘do’ anything to shape or directly inform a higher-level computational theory, and it can potentially be involved in any number of mental functions. Brain dynamics, on the other hand, are by definition far more constrained: A single γ cycle, for instance, cannot be claimed to be responsible for processing a verb phrase purely because of its narrow temporal window. In addition, claiming that a given portion of Broca’s area is “responsible

for interpreting word movement” (as is often done) is hellaciously bad biology, and only serves to give credit to a syntactic/processing theory rather than contribute to an understanding of brain and language function.² We spend our time well when we reconsider the conclusions of Ojemann (1990), who showed that while distinct features of language propagation are strictly localized, such loci are *temporary* and display great individual variability, with the neuronal functions changing over time, and so we can only ever conclude from neuroimaging experiments that cell assemblies are active in particular tasks *at time T, under condition P*, and can at best be specified for particular functions.

The most advanced experimental evidence B&C put forth is Musso et al.’s (2003) seminal work on nonsense languages obeying UG principles, which they say “elicit normal activation in the language areas of the brain” (p. 106). The misleading term “language areas of the brain” reflects the general level of disengagement the authors adopt towards all the “important biological questions” (p. 1) which “arise” from an exploration of the Basic Principle’s implementation in the brain. It is certainly odd that B&C can write that “some small rewiring of the brain provided the core element of the Basic Property” (p. 107)—without even attempting in chapter 4 (putatively focused on brain structure) to cash this out in implementational terms. Pointing to a relatively dense, large regional structure like the middle temporal cortex and stating that it is where “the lexicon” is housed is similar to if Stephen Hawking sat under a dark star-filled night sky, pointed very roughly somewhere up at space, and claimed, “There’s a black hole over there somewhere”—a statement which tells us nothing about black holes nor anything about space. In fact, Hawking would be on much firmer ground than B&C, since at least he can provide a theory of his object of study which can be embedded within a larger framework of quantum effects.

The strikingly basic neurobiology and cortico-centrism presented in much neurolinguistic work is incompatible with what is known about the brain and its principal dynamics. As a novel approach, from the perspective of brain dynamics what B&C call “some algorithm” responsible for labeling becomes capable of being explored in a number of interesting ways. Neural oscillations might be a suitable way of exploring mesoscopic computations across a number of cognitive faculties, as is already being done in domains outside of language like working memory. Consider a relatively simple example. The model of linguistic computation in Murphy (2015d) invokes a number of cross-frequency coupling operations, and in Benítez-Burraco & Murphy (2016) current knowledge of the linguistic and ‘oscillopathic’ profile of individuals with autism was used to empirically test it. It is additionally of interest, for instance, that schizophrenic

² We might conclude from this that there are really only two types of people in the world: *neurolinguists* and *neurolinguists*. Too often is the brain used to ‘back up’ a given linguistic theory by the former, while general theories of language are sometimes used by the latter to support a particular neuroscientific model. Meanwhile, both brain structure and linguistic computational competence remain locked in different cells on different floors of different prisons, unable to communicate or help each other escape. These approaches seem to confirm the beliefs of some medieval philosophers who thought that the insufficiency of human logic would result in barriers to naturalistic understanding (O’Meara 1982)—although it’s not really human ‘logic’ which is causing the problems here, rather cross-disciplinary prejudices.

patients showed higher α - γ cross-frequency coupling in Popov & Popova's (2015) recent study of general cognitive performance, despite this co-varying with poorer attention and working memory capacities. This is surprising given that most studies show reduced left frontal γ in schizophrenia. The reason for this may be that the increased phase-amplitude-locking likely results in smaller 'gamma pockets' of working memory items (as Korotkova et al. 2010 argue on independent grounds) and hence low total γ power. In this instance, the size and order of working memory sequences outputted by the conceptual system is not optimally compatible with the oscillopathic profile, leading to greater rhythmic excitability and yet inhibited linguistic functionality. Global rhythmicity is consequently disrupted due to unusually strong fronto-parietal interconnectivity.

This may represent a genuine neural mechanism of an 'interface' between syntactically generated conceptual representations and external (memory) systems; a significant finding, if corroborated by further experimental work. Importing standard assumptions from syntax, we can think of the computational system as imposing its own conditions on the interfaces. The shift in perspective to oscillatory terms allows us to reformulate this such that the neural ensembles responsible for storing representations used to construct phrases require particular phase-amplitude-locking levels in order for the interconnected regions coupled with them to 'read off' their content. Studying what we could call the human 'oscillome' may provide an excellent way of experimentally investigating what kind of features can 'pass through' the interfaces, and because each rhythm plays numerous, non-overlapping roles, it is crucial for these oscillopathic studies to be accompanied by biophysical modeling and computationally explicit mesoscopic frameworks of regionally localized cross-frequency coupling functionality.

Over the past couple of years, the oscillation literature has shown great promise in exploring some major topics in linguistics (Ramírez 2015). Recent studies of α have shown that listeners who show better attention-to-memory capacities show more flexible α power allocation, leading to the suggestion that "selective attention to a specific object in auditory memory does benefit human performance not by simply reducing memory load, but by actively engaging complementary neural resources to sharpen the precision of the task-relevant object in memory" (Lim et al. 2015: 16094). Just as John O'Keefe and colleagues have shown that fast γ rhythms can compute vectors in the mouse hippocampus for spatial navigation (Chen et al. 2013), it may be that this generic oscillatory mechanism is employed in the service of constructing language-relevant feature-sets. The absence of a complete dorsal-ventral stream 'loop' in the macaque brain (Frey et al. 2014) appears to be only the briefest sketch of the real underlying puzzle, and could be incorporated well into a larger oscillomic system invoking, among other things, human-specific myelination rates as a way of directly modulating the phase and power of oscillations (Pajevic et al. 2014).

Ding et al. (2016) showed that distinct rhythms entrain to distinct grammatical constructs, from words to phrases to sentences, with slow rhythms in the parietal lobe, superior temporal gyrus and inferior frontal cortex entraining only to phrasal and sentential structures, not syllabic ones. There have been many quibbles raised recently about the experimental materials, controls, number of participants and so forth, as indeed there should be. But there has been little

discussion about the actual implications of this study for cognitive and linguistic architectures more generally. Following other seminal work by David Poeppel's group on the dynamics of phonological computation (e.g. Giraud & Poeppel 2012) and Lisman & Jensen's (2013) hypothesis that items from working memory are extracted via θ - γ embedding (which dates to the mid-1990s), we could draw up an 'oscillomic' hypothesis for the construction of linguistic feature-sets (Figure 1) which would directly enrich B&C's cartographic perspective.

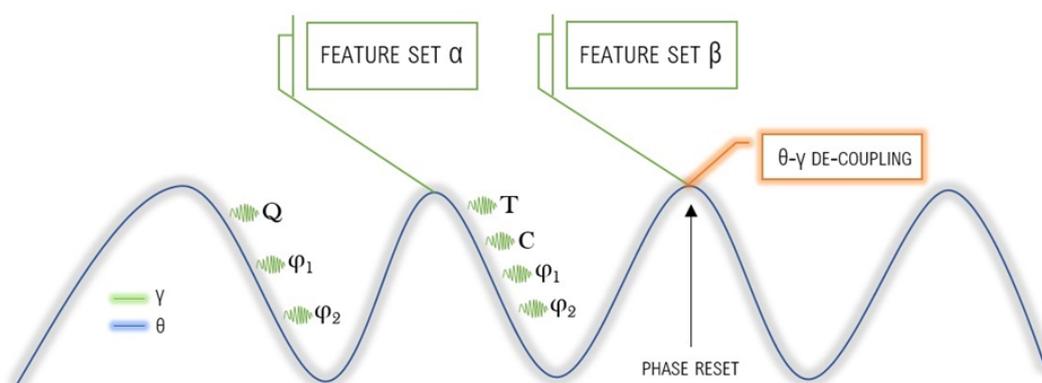


Figure 1: An idealized model for feature-set retrieval. 'Q' denotes Q-feature, 'T' denotes Tense feature, 'C' denotes Case feature, and ' ϕ ' refers to ϕ -features (Person, Number, Gender).

In Figure 1, after inhibition reduces over the θ cycle, the most excitable representation would be itemized through low-middle γ , followed sequentially by the other, less excitable clusters. This would determine feature-set composition, completed after the θ phase resets. The 'lexicon' may amount to stored time-frequency profiles, with each item being composed of particular, sequentially excited and 'binded' feature-sets (although see below for a qualification of this term). Recent work (Chomsky 2015) has also argued that linguistic structures can be labeled not only by standard categorial labels, but also by ϕ -features, as in [ϕ ... α ... [γ ... β ...]], expanding the oscillomic search range. Derivational feature-checking (e.g. ϕ -feature agreement followed by Q-feature agreement within the same phase) may arise from the particular sequence of items extracted within a given oscillatory cycle. The set of feedforward γ rhythms employed in this model would be mostly generated in supragranular cortical layers (L2/3) (Maier et al. 2010), while hippocampal θ would be generated via slow pulses of GABAergic inhibition as a result of medial septum input, part of a brainstem-diencephalo-septohippocampal θ -generating system (Vertes & Kocsis 1997). The interactions between the hippocampus and medial prefrontal cortex necessary to focus attention on language-relevant features (considering the conclusions of Lara & Wallis 2015 on the role of prefrontal cortex in working memory, which stressed the centrality of attention rather than storage) may be mediated through an indirect pathway passing through midline thalamic nucleus reuniens (Jin & Maren 2016).

External constraints would also influence the temporal serialization of feature extraction: Ray & Maunsell (2015) note that the coordination of γ phases

across multiple, distant areas is difficult due to conduction delays, mediated by myelin thickness and nodal structure. For instance, a conduction delay of only 5ms could change the interactions of coupled γ oscillators from constructive to deconstructive interference (Pajevic et al. 2014); see also Nevins (2016) for related discussion of feature composition and motivations for assuming that Number and Person features do not combine via symmetric conjunction but rather through specific orders, possibly grounded in the above oscillomic mechanisms. Finally, while Ding et al. (2016) explored the rhythms responsible for ‘packaging’ particular constructions, their top-down experimental approach has its limitations, since the functional role of these rhythms in cognition more generally needs to be explored alongside broader research into the oscillatory nature of working memory, attention, and other domains necessary for language comprehension.

This idea could be developed through the construction of an ‘oscillomic tree’, in contrast to standard linguistic tree structures (Figure 2).

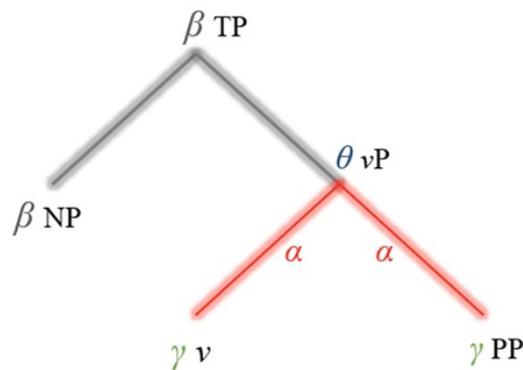


Figure 2: An oscillomic tree representing the putative rhythms responsible for particular lexical and phrasal structures according to Murphy (2015d). ‘TP’ denotes Tense Phrase, ‘vP’ denotes Verb Phrase (e.g. ‘swam in the river’), ‘NP’ denotes Noun Phrase (e.g. ‘The man’, ‘John’), and ‘PP’ denotes Preposition Phrase (e.g. ‘in the river’).

In Figure 2, at the point of v –PP concatenation generated by γ and coupled to θ , β maintains previous phrases in memory and embeds subsequent γ cycles, permitting the binding of phrasal constituents into a larger structure. As discussed in Murphy (2015d), α is likely involved in embedding cross-cortical γ , a form of set-formation, and is possibly generated in the thalamus (see Crandall et al. 2015 for evidence of neocortical control of thalamic gating, enhancing the role of the thalamus in higher cognitive functions). Spatio-temporal patterns of processing syntactically complex, memory-demanding sentences result in left parietal α increases, while higher β was found for long- relative to short-distance dependencies (β is more generally implicated in the maintenance of existing cognitive sets; Engel & Fries 2010). A possible reason for this is that the greater working memory load needed to resolve long-distance dependencies requires a higher frequency band to synchronize the cell assemblies implicated in the feature-sets of the filler and gap; certain assemblies would be pre-activated by the

filler (since dependents share a sub-set of their features). Because γ is modulated by cloze probability (Wang et al. 2012), β - γ synchronization may be the central mechanism of feature-set binding within phrase structures, with γ being responsible for semantic prediction and feature-binding (compositional meaning) and β being responsible for syntactic feature-binding and object maintenance (monotonic labeling).

Human-specific diverse phase relations (Maris et al. 2016) would also permit a greater degree of featural 'size' via the range of cross-coupling information gating, and may also permit different ϕ -features to 'probe' in unison (van Urk 2015). Similar approaches (accompanied by hodological research into the pathways responsible for a given cross-frequency coupling relation) could be taken to the various monkey oscillomes, attributing distinct rhythms and phase-locking patterns to particular call sequences (Murphy forthcoming). B&C's observation that syntax appears to operate via structural and not linear distance when constructing dependencies may also emerge from temporally distant cross-frequency couplings, such that an ensemble storing a given representation may be more closely coupled (via 'cycle skipping', controlling the activation of particular cell assemblies; Brandon et al. 2013) to a rhythm activating temporally distant ensemble X and not the rhythm responsible for the temporally closer ensemble Y.

In the above model, bottom-up γ would rapidly shift the ongoing set of featural representations through a standard feedforward mechanism, updating hippocampal θ and the widely distributed inter-areal β . The responsibility for linking distinct cortical areas into NeuroCognitive Networks (NCNs; Bressler & Richter 2015), or large-scale, self-organizing cortical networks, likely falls to β . Bressler & Richter claim that this rhythm plays dual roles, being implicated in NCN maintenance and transferring top-down signals to lower levels in the cortical hierarchy (e.g. the γ range). This model is compatible with the need for phrases to be labeled via two (domain-general) sub-processes: object maintenance (keeping the constructed set in memory) and property attribution (affording the set an independent computational identity), since β would be able to simultaneously maintain an object as a cognitive set (via its steady or increasing amplitude) and attribute a specific representational property to it (via top-down feedback and transferring prediction signals).

Similar studies of infant and child language processing will also be crucial, since the developmental characteristics of the oscillome are far from well understood. To take one of the very few current examples of this, Schneider et al. (2016) recently showed θ and β power decreases in adults at, respectively, left frontal and parietal sites and right parietal sites during the processing of ungrammatical sentences. These global(ur), dynamic concerns also speak to Gallistel & Matzel's (2013) assessment that, as a fundamental mechanism of synaptic transmission, the properties of long-term potentiation cannot explain the properties of associative learning and memory. As Fitch (2014: 392) writes, we should be "under no illusions that the theory of computation, with its stacks and queues and rewrite rules, provides anything even close to a final model of biological computation". Along with being able to describe how the brain performs large-scale inter-regional computations (potentially moving towards alleviating Fitch's anxiety),

oscillomic phase hierarchies may support the extraction of morphological representations (see Leong & Goswami 2015 for related discussion).

In modern humans, there is increased fronto-cortical connectivity and a more developed role for the subplate in achieving this, which likely altered the structural and functional role of cortical γ oscillations. The evolution of the subplate additionally aids language network inter-connectedness, which relies not only on axon pathways but on the synchronous firing of cortical cell assemblies transmitting information between each other (although in what format this 'information' is stored remains unclear). This gives rise to γ , essential for higher cognition. Relatedly, fast-spiking interneurons such as chandelier cells play an enhanced role in humans relative to other species, aiding the cortex in transmitting longer sequences of information (Molnár et al. 2008). Different interneurons can compete to generate the same γ rhythm, as Clowry (2014: 227) summarizes:

The degree of involvement of each cell type dictates the frequency of the network rhythm within the gamma band. This ability to switch between frequencies opens up the possibility for a group of neurons to bind with different neuronal assemblies depending on which frequency channel was in operation. Potentially, the greater the repertoire of interneurons present, the greater is the potential number of channels of communication.

There is a dense literature, then, on the functional role of brain rhythms in a number of cognitive domains, and which could inform major debates in the field. For instance, Jensen et al.'s (2012) approach to the visual system's prioritization of salient unattended stimuli claims that γ rhythms phase-lock to posterior α - and β -oscillating regions to form a clocking mechanism sequentially activating particular visual representations, such that object X in a given scene is interpreted before object Y, imposing general cognitive set-constructing rules of efficiency. If similar oscillomic mechanisms are responsible for linguistic feature-set composition, then this could potentially provide a way of neurobiologically grounding the principles of Relevance Theory, through which particular representations are claimed to be triggered before others due to their 'cognitive relevance'. Cross-frequency coupling may consequently be able to connect segmentation/parsing with representation decoding/interpretation, with oscillations (implementation) being the mechanism to address segmentation (computation) via a phase-resetting (algorithm).³ Instead of coming up with new names for the 'Language/Logic of Thought' (*à la* Hauser 2016) or tweaking and re-re-revising the odd model of the Italian left periphery and addressing other computational concerns, it may be more beneficial (both to linguistics and the brain sciences) if efforts were instead made to discard as much of the "attendant logico-philosophico-mathematical baggage" (Tomalin 2006: 188) carried by modern linguistics and re-translating or re-embedding only the bare minimum required for hierarchical phrase structure building into the rest of the biological and neurophysiological sciences.

³ This type of multi-dimensional perspective on language can already be found in Bechtel's (1994) model of 'mechanistic explanation', in which different levels of description are composed of discrete entities with causal-explanatory force between each level.

This will also undoubtedly ‘free’ linguists from investigating the computational system from such a narrow perspective. For instance, given the minimalist framework provided to him, van Urk (2015) sensibly eliminates the A/A’ position distinction and replaces it with obligatory A-features (ϕ -features) and optional A’-features (*Wh*, *Top*, *Rel*, and so forth). But where does this A/A’-feature distinction come from (a question which seems to me just as problematic as how A/A’-positions emerge)? Examining the oscillomic nature of these features would deliver a ‘bottom-up’ account of how they emerge and what their limits of interaction and generation are. Computational studies can undoubtedly (though only partly) direct oscillomic hypothesis formation, but I hope by now it should be clear that sticking purely to recycling and refining feature-based models of Merge-based grammars will not result in an adequate theory of linguistic competence: Syntacticians will simply never be able to know whether a given input-output derivational system properly characterizes the human language faculty until they explore its hardware.

Oscillation-based linking hypotheses might also provide a substantive response to Revonsuo’s (2001: 51) comment that in contemporary neuroscience, “the main efforts are concentrated on the description and systemization of data and the utilization of the data for clinical purposes. No radically new theoretical purposes, comparable to the neuron doctrine, have emerged from this enterprise as yet”. As Snyder (2015) reviews, oscillations are increasingly being shown to play a causal, and not correlational role in the perceptual segregation of sound patterns (though it should be stressed, as Snyder does not, that numerous other oscillatory mechanisms likely do not play a causal-functional role in cognition).

The unfortunate influence of Marr Misreaders has discouraged linguists from engaging with this literature, with cognitive neuroscience oscillation research perhaps being initiated properly over a quarter of a century ago by Gray & Singer (1989), who discovered that, when multiple features of a visual scene were interpreted by an individual as belonging to the same object, the neuronal temporal impulses were synchronized in the regions assumed to subserve each featural component. I think the potential for these mechanisms to explore, and perhaps even constitute part of, the language faculty is substantial; indeed, Gray & Singer were surprised by oscillatory coupling at neuronal groups 7mm apart, but by now it has been well established that coupling can occur at much greater distances, and so the potential explanatory scope of the oscillome has dramatically increased over recent years.

Crucially, the information synchronized by the striate cortex is discrete, and so it makes little sense to talk (as is very often done) of features ‘combining’ in the brain to form a coherent representation. Similar things presumably apply to the present model of linguistic computation: To understand a word is simply to comprehend a given set of features, and it is superfluous to invoke an additional ‘binding’ mechanism on top of rhythmic synchronization. Cross-frequency coupling simply *is* the binding mechanism. The mind is sensitive to whichever features cross-frequency coupling operations can excite. Neither seeing a table nor interpreting the word *table* require a further procedure to ‘construct the image of a table’ or ‘construct the meaning of *table*’. To see a table is not to ‘bind’ its legs and arm rests and color and size and edges—it is rather to

see/excite these features in synchrony. Similarly, to know a language is not to ‘combine’ language-relevant features triggered by some modality, it is rather to sequentially excite them, yielding a conscious representation which we may, for convenience, term a ‘binded’ one.

Finally, studies of the human oscillome could provide an elegant way of grounding some recent proposals about ‘third factors’ in language design. Using Laplacian Eigenmodes to analyze MRI and DTI data, Atasoy et al. (2016) demonstrate that resting brain function is related to brain shape. They argue that “the critical relation between the neural field patterns and the delicate excitation–inhibition balance fits the neurophysiological changes observed during the loss and recovery of consciousness”. The eigendecomposition of the Laplace operator may provide fundamental principles permitting a direct macroscopic description of collective cortico-cortical and thalamo-cortical dynamics. The spatial harmonic waves they observed seem to predict resting state networks and obey the same physical principles as other self-organizing phenomena (such as tiger and zebra stripes or the patterns of vibrating sand), lending support to Descartes’s original intuition that the brain is organized through principles of “efficient causation”, and not being incompatible with recent work in generative grammar suggesting that syntactic computation operates via principles of efficient computation (Narita 2014).

While most of the topics of language evolution (like language use) do indeed remain in the dark, I hope to have shown that some—given the right multidisciplinary perspective—are becoming increasingly tractable. If feature-set binding, object maintenance, property attribution, featural comparisons, and cross-modular searches are experimentally found to be implemented via generic oscillomic sub-routines and various cross-frequency coupling relations, this would be a substantial step towards understanding the biological basis of language. Research into the human oscillome’s neurochemical and genetic basis is rapidly expanding, widening the scope for interdisciplinary investigations into its lower-level implementation and origins. Although this work is not formally described as ‘language evolution’ literature, given the promising directions open to oscillomic experimental and theoretical work it may not be all that long until studies of thalamic α and frontal γ are considered contributions to the implementational basis of phrase structure building. An underlying impetus for this burgeoning language evolution literature was touched on by Gérard Wajcman, who as a Lacanian scholar and a figure far from evolutionary biology consequently serves as an appropriately disconnected departure from an analysis of a (currently) disconnected oscillome:

We are animals sick with language. And how sometimes we long for a cure. But just shutting up won’t do it. You can’t just wish your way into animality. So it is then, as a matter of consolation, that we watch the animal channels and marvel at a world untamed by language. The animals get us to hear a voice of pure silence. Nostalgia for the fish life [...] We record whales singing their whale songs capable of transmitting messages to other whales thousands of kilometers away, but in truth, brandishing our microphones, we only aspire to one thing—that those whales would sing us a song.

(Wajcman 2009: 131)

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