

Interfaces (traveling oscillations) + Recursion (delta-theta code) = Language

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ABSTRACT Formulating a minimalist model for language, Gärtner and Sauerland (2007) collected a series of papers exploring the possibility that the recursive generative component plus the conceptual and articulatory interfaces provide the essential components of the system. This was summarized as ‘Interfaces + Recursion = Language’. Over the past decennium a range of linking hypotheses have been drawn up to better ground this architecture within the brain. In the realms of cognitive and systems neuroscience, the search for the neural code across a number of domains has seen a marked transition from the analysis of individual spike timings to larger patterns of synchronization. This chapter argues that the language sciences should embrace these systems-level developments, with recent findings concerning the scope of possible oscillatory synchronization in the human brain revealing the existence of traveling/migrating oscillations, adding further impetus to reject the typical stasis found in cartographic neurolinguistics models. After exploring empirically-motivated revisions to the neural code for hierarchical phrase structure, it is discussed how this code could provide a new perspective on language disorders, fluid intelligence and language acquisition.

KEYWORDS delta, gamma, language disorders, neural oscillations, weakly coupled oscillators

1 INTRODUCTION

This chapter will be concerned with the neural implementation of the generative component of language. Specifically, it will discuss the potential neural oscillations have for providing an explanatory link between linguistics and the brain sciences. *Neural oscillations* are rhythmic fluctuations of spiking activity within neural clusters, and in recent developments in cognitive neuroscience it has been argued that synchrony of these oscillations in distinct clusters can shape input gain and assist information transfer (Akam & Kullmann, 2010; Muller et al., 2018). Oscillations reflect synchronized fluctuations in neuronal excitability and are categorized by frequency: delta (δ : ~0.5–4 Hz), theta (θ : ~4–8 Hz), alpha (α : ~8–12 Hz), beta (β : ~12–30 Hz) and gamma (γ : ~30–100 Hz) (see Meyer, 2017).

With respect to particular language-neurobiology linking hypotheses, I will here be assuming the framework for phrase structure generation in Murphy (2016a-c), involving, at a minimum, $\{\delta(\theta)\}$ phase-amplitude coupling (with the notation denoting the amplitude of θ being phase-locked to δ) to construct multiple sets of linguistic syntactic and semantic features, with distinct β and γ sources also being embedded within θ for, respectively, syntactic prediction and conceptual binding. This provides a specific neural code for *recursive hierarchical phrase structure* (reapplying the set-forming operation to its own output), with α being involved in the early stages of binding (Pina et al., 2018) to synchronize distant cross-cortical γ sites needed for the ‘ $\{\theta(\gamma)\}$ code’ of working memory and to modulate attentional resources. True recursion defines its output value in terms of the values of all of its previous applications, grounded in the initial application (Lobina, 2017), and this self-referential quality of recursion can be implemented via repeated nestings of θ within successive δ rhythms. The $\{\theta(\gamma)\}$ code is a generic mechanism utilized for visual, auditory, somatosensory and even vibrotactile working memory (von Lutz et al., 2017), and is also involved in inter-regional communication (Solomon et al., 2017), and so it is likely recruited by the language system. θ - γ phase-phase coupling in the human hippocampus has also been shown to be involved in multi-item working memory maintenance (Chaieb et al., 2015), and different cognitive domains may construct representational stacks via different types of couplings. Given the rich inter-

faces between language and other cognitive and perceptual domains, it is likely that language processing is implemented via a range of cross-frequency couplings. Although there is accumulating empirical support for this model (Segaert et al., 2018, provide empirical support for the present claims about α being involved in phrasal chunking) and its computational basis (Zaccarella et al., 2017, provide neuroanatomical support for assuming a core, elementary phrase-structure building operation), recent research opens up the possibility for expansion and refinement.

I would like to note here that any particular linguistic theory which assumes elementary combinatorics for syntax in conjunction with some form of cyclically generated hierarchical phrase structure is compatible with the model to follow, and there is nothing (as yet) in principle which should restrict our focus to *generative/minimalist models* – not least because neurobiological theories do not yet have the explanatory power to adjudicate between different computational theories. Hierarchical dependencies are not exclusive to generative theories, and there is potential scope for linking hypotheses between neurobiology and any number of linguistic theories (e.g., Categorical Grammars, Dependency Grammars, Usage-Based grammars). The minimalist framework assumed here is motivated primarily by the architecture formulated by the Gärtner and Sauerland (2007) equation mentioned above, which is particularly useful for integrating distinct neurobiological processes into a unified theory of the dynamics of language comprehension.

2 TRAVELING OSCILLATIONS

Building on a large body of work into the nature of oscillations (Kopell et al., 2014; Le Van Quyen & Bragin, 2007; Patten et al., 2012), Zhang et al. (2017) present novel insights into a relatively new mechanism for large-scale neural coordination in the form of *traveling oscillations* which cycle cross-cortically at a speed of $\sim 0.27\text{--}0.75$ metres per second. These form spatially coherent waves that move across the cortex. In purely physical terms, a traveling wave is a disturbance traveling through a medium such as water, air or a cellular network. Instead of involving precise zero-lag synchrony (involving perfect temporal alignment between synchro-

nized oscillations), Zhang et al. show how a range of phase offsets can be achieved (whereby the phase of multiple oscillations differs), producing traveling waves of various shapes such as plane, radial and spiral waves. The propagation of traveling oscillations was found in 96% of neurosurgical patients (through electro-corticography) and was consistent with good performance on the Sternberg working memory task (Sternberg, 1969). Zhang et al. (2017, p. 3) conclude that “human behaviour is supported by ... traveling waves”. These waves have recently been implicated in multiple sensory, motor and cognitive systems, and Muller et al. (2018, p. 1) recently speculated that “travelling waves may serve a variety of functions, from long-term memory consolidation to processing of dynamic visual stimuli”. Summarizing recent literature, Muller et al. (2018, p. 8) suggest that hippocampal CA1 traveling waves in the θ band exhibit a particular computational role (“Patterning pyramidal spiking from small to large place fields in each theta cycle”) which can be contrasted with the putative role of traveling fast γ waves in the same region (“Patterning spiking in either direction of the dorsoventral axis in hippocampus”). More broadly, it seems clear that traveling waves serve to organize spike timing along a particular behaviorally relevant axis.

It is clear from Muller et al. (2018; see their Table 1) that only visual, sensorimotor, motor, hippocampal and macroscopic computational principles of traveling waves can be proposed with any certainty, with the development of large-scale, high-precision recording technologies being able to expand current understanding. What precisely constitutes the range and influence of traveling waves over the rest of cognition is a topic for future study, and Muller et al.’s project should readily be expanded to language processing such that neurolinguists should investigate the computational role of traveling waves across various *language regions*. For now, we can begin to sketch possible directions and explanations for these discoveries.

Zhang et al. (2017) discovered what they define as traveling *theta and alpha oscillations*, yet their analysis reveals that the full range of migrating waves stretched from 2–15Hz, therefore implicating mid- δ . Mid- δ is involved in phrasal chunking, though not sentential chunking (which low- δ seems responsible for). This could potentially lead to a refined neural code for language processing: δ waves cycle across the cortex, building up the syntactic representation phrase-by-phrase and being en-

dogenuously reset by a newly constructed phrase, either traveling to parts of the cortex responsible for storing the required semantic representations or being coupled to traveling θ waves which perform the same function. The second option seems more likely, given what is known about where δ seems to be localized during language comprehension (Ding et al., 2016). The limitations of semantic processing could be derived either from the physical limitations placed on the speed of traveling cycles as they move from station to station ($\sim 0.25\text{--}0.75$ m/s) or the width of the propagating waves (median: $\sim 2.4\text{--}4.8$ cm) which might limit the range of conceptual structures manipulated.

As discussed elsewhere (Murphy & Benítez-Burraco, 2017a), the brain was re-shaped in our lineage via *globularization*, through which our braincase adopted a more globular shape, and so I would like to hypothesize that this granted oscillations the ability to travel across new areas of the cortex and subcortex whilst also being coupled to a number of other regions. This would have opened up new interfaces for conceptual representations, and in combination with the present neural code would also have derived Gärtner and Sauerland's (2007) equation *Interfaces + Recursion = Language*. Further, Zhang et al.'s findings support a model of traveling waves as a network of *weakly coupled oscillators* (WCO), according to which the traveling wave is a result of phase coupling. According to the WCO model, oscillators are arranged in a linear array and are weakly coupled with their neighbors. The model also assumes that there is a spatial gradient in intrinsic frequency across the oscillators. Since the traveling wave is assumed to be the result of phase coupling, these assumptions conspire to yield the prediction – fulfilled by Zhang et al.'s (2017) data – that faster waves would travel in the direction of slower waves. The language model assumed here (see also Murphy, 2015) complements these findings, since Zhang et al. found that waves typically travelled in a posterior-to-anterior direction. It is assumed here that elementary syntactic combinatorics involves a parahippocampal and cortico-basal ganglia-thalamo-cortical loop (concatenation and semantic conjunction) which is later coupled with left inferior frontal regions such as BA 44 and BA 45 which act as crucial memory buffers for the maintenance of hierarchically organized syntactic objects.

Both this model and the WCO traveling wave model predict posterior-to-anterior directionality as the language system proceeds from se-

lecting linguistic features (parahippocampal, thalamic and basal ganglia regions), to combining them (anterior temporal regions), to attributing to them a labelled identity (cortico-basal ganglia-thalamo-cortical loop), and finally to storing them in working memory (left inferior frontal regions, in particular pars opercularis). This directionality also notably correlates with the rhythms hypothesized to be responsible for these operations, with faster γ and β rhythms in posterior and central regions being coupled with slower central θ and α rhythms, which in turn travel towards slow left inferior frontal δ regions they are coupled with. While faster γ and β rhythms have currently not been shown to migrate, we can assume that this reinforces the neuroanatomically fixed nature of conceptual representations as being stored in typically resilient neural clusters (= *representations*), which can nevertheless be coupled to slower, traveling rhythms (= *computations*).

More pertinently, Zhang et al. (2017, p. 13) conclude that “[w]hen phase coupling is absent, there are no traveling waves because intrinsic oscillation frequencies differ between electrodes”. This suggests a strong degree of co-dependence between the phenomenon of cross-frequency coupling and traveling waves. If certain findings reviewed in Murphy (2016c) are accurate – in particular, the finding of human-specific phase coupling diversity, hypothesized here to have occurred due to cranial re-shaping – then the language system likely evolved as a direct outcome of a broader range of oscillatory migration routes which resulted from new inter-regional phase couplings. One of language’s hallmark characteristics of breaking modular boundaries and combining representations from distinct domains to be stored cyclically in an expanded memory buffer (or phonological loop; Aboitiz, 2017), would arise immediately from this – as would the language system’s ability to interface with conceptual and articulatory apparatuses. Though I have explored elsewhere how the core oscillatory architecture of δ - θ - γ interactions can generate phrase structure building (e.g., Murphy, 2016c), the work of deriving the mechanism of syntactic combinatorics was previously left simply to phase-amplitude coupling. We can now add to this basic mechanism the understanding that language-relevant representations can be accessed cross-cortically through a process of posterior-to-anterior wave propagation.

Concerning the topic of what type of grammatical representations are manipulated by the brain, Greenhill et al. (2017) used a *Dirichlet process mixture model* (a probability distribution whose range is itself a set of probability distributions) to explore the rates of change in lexical and grammatical data from 81 Austronesian languages, showing that while many features change rapidly there exists “a core of grammatical and lexical features that are highly stable” (2017, p. e8822), and hence are strong candidates for being central components in the dynamics of language evolution. These stable features include inclusive vs. exclusive distinctions, gender distinctions, the existence of tense auxiliaries, prepositions, clause chaining and the presence of animacy features on the noun/class gender system (see Dataset S2 in Greenhill et al., 2017). Recent work has revealed that different cortical regions appear responsible for storing distinct representational formats, with γ rhythms in the ventrolateral prefrontal cortex signaling low-level, stimulus-based category abstraction (e.g., dog) and β rhythms in the dorsolateral prefrontal cortex signaling high-level, rule-based category abstraction (e.g., animal, Wutz et al., 2018). A slight reorganization in the shape of the prefrontal cortex (of the kind discussed in Neubauer et al., 2018) may have permitted the brains of anatomically modern humans to generate oscillatory migrations and phrase synchronizations such that these two major ontological representational bases could interact more efficiently, potentially allowing the generation of a greater number and broader range of low-level categories to be stored within a given high-level node.

Since the poster-to-anterior propagations documented in the literature are involved in *feedforward processes*, it is possible that instances of anterior-to-posterior migration (a phenomenon documented in Zhang et al., 2017, and which was extremely rare compared to the reverse migration pattern) have a distinct functional role such as supporting feedback or top-down processes. It would be of interest to explore in future work whether δ waves propagate in an anterior-to-posterior direction at particular points of syntactic processing, perhaps accessing distinct loops of a memory buffer stretching from pars opercularis to posterior regions of Broca’s area as the number of syntactic labels/nodes increases. Moreover, these findings should encourage neurolinguists to reconsider some core assumptions considering event-related potentials, which might (under the present framework) result from traveling waves transiently

organizing at a given timepoint and phase (see also Murphy, 2015, for connections between oscillations and event-related potentials).

If δ rhythms are shown to migrate during phrase-structure building, it would be possible to attribute particular computational roles to these oscillations in the way Muller et al. (2018) have done for spatial navigation. For instance, traveling δ waves could be responsible for patterning spiking from single- to multi-unit lexical structures in each δ cycle.

In my view, these observations speak against the idea that linguistic computation is based on *regional stasis* (e.g., the claim in Friederici et al., 2017, that BA 44 and its temporal dorsal pathway constitutes the basis of natural language syntax) and is rather implemented via a cortical circuit even more dynamic than previously assumed (for perspective: Zhang et al., 2015, discovered for the first time traveling θ waves, but only throughout the human hippocampus; see also Patten et al., 2012). Indeed, Muller et al. (2018, p. 12) note that “the existence of stimulus-evoked traveling waves in the sensory cortex presents a challenge to the orderly topographic arrangement of selectivity first described by Hubel and Wiesel at the trial-averaged level”. Likewise, the existence of weakly coupled traveling oscillators presents quite a dramatic challenge to the language sciences, and it has been my intention here to sketch out possible directions for reconciling the cortical language circuit with these emerging discoveries and principles.

Current neurolinguistic work on brain oscillations provides simple associative oscillation-computation models mapped to strict brain regions, as when Meyer (2017) claims that β is strictly involved in prediction, or when Ding et al. (2016) propose that δ entrainment to phrasal and sentential structures is a core feature of language comprehension, or when Bastiaansen and Hagoort (2015) claim that γ is involved in semantic unification and β is involved in processing syntactically coherent structures. All of these studies doubtless shed some light on the dynamics of the cortical language circuit, but they should be understood to be only a partial take, with the existence of traveling oscillations potentially forcing a more elaborate set of models to emerge.

It may not simply be oscillations, then, but more specifically traveling oscillations that could provide the optimal way to bridge neuroanatomy and brain dynamics, fulfilling the goal articulated succinctly in Friederici et al. (2017, p. 719) of “finding the explanatory link between the neuro-

anatomical data, the electrophysiological data, and the formal properties of human syntax”. As Zhang et al. (2017, p. 15) conclude, “individual traveling-wave cycles represent spatially discrete pulses of neural activity that correspond to distinct behavioral states”. The future task for the language sciences is to investigate how traveling waves might serve as a general mechanism for transmitting discrete pockets of neural activity in ways which map onto the functions of semantic, phonological and syntactic combinatorics. Muller et al. (2018, p. 1) document “the generality of their role in cortical processing” but their role in language processing remains unknown. Indeed, in their original discovery of traveling waves, Patten et al. (2012, p. 7) speculate that “the thalamus may exert an important influence on cortico-cortical propagation via thalamocortical re-entrant loops”, and since traveling waves appear to propagate along corticocortical fibers the role of the thalamus may be crucial (see Murphy, 2015, for the role of the thalamus in language).

3 **RETHINKING LANGUAGE DISORDERS, FLUID INTELLIGENCE AND LANGUAGE ACQUISITION**

Traveling oscillations may also be able to account for certain *language disorders* and *aphasias*, since in the literature there are often cases documenting damage to brain areas not typically seen as *language areas* (see also Luef in this volume) and yet which negatively impact language processing (Papathanasiou et al., 2012). It is possible that the migration of oscillations is disturbed by lesions and other forms of brain damage, which may serve to *block* them. Likewise, there are an even greater number of documented cases regarding the survival of key language skills after a supposedly core language region is damaged (see Ardila et al., 2016). Under the present perspective, this could simply imply that only part of the migration route was taken, impairing some representations from being accessed but nevertheless leaving much intact, or indeed that only part of the migration route was damaged. It is well known, for instance, that *Broca’s aphasia* can be caused by damage to a number of areas outside Broca’s area, such as the superior longitudinal fasciculus (see papers collected in Bastiaanse & Thompson, 2012). Lesions to the precentral gyrus,

anterior insula, and even the basal ganglia and anterior temporal lobe have been implicated in Broca's aphasia (Abutalebi & Cappa, 2008). Crucially, notice that these structures lie along the broader language circuit implicated in the model in Murphy (2016a-c), suggesting that damage to different stations of the path taken by language-relevant traveling oscillations (mediated necessarily by connecting neural streams) can result in aphasias just as severe as those resulting from damage from more classically *core* language regions. Disruption of the anterior head of the caudate and putamen results in verbal aphasias (Lieberman, 2000), which may be due not simply to damage to white matter fibers projecting from the cortex to the striatum (*à la* Nadeau & Crosson, 1997) but more specifically because oscillations responsible for constructing necessary speech signals are blocked from traveling across the full network responsible for vocal production, extending far beyond the thalamus (it should be noted that transmission speed in cortical gray matter is estimated to be approximately 1000 times slower compared to white matter, pointing us towards likely sources of linguistic computational efficiency; Kurth et al., 2017). A similar explanation might account for the various verbal communication deficits resulting from lesions to the globus pallidus (Strub, 1989). A possible way to provide some criteria of falsification for these hypotheses would be to conduct magneto-encephalographic (MEG) or electro-encephalographic (EEG) scans of participants with various aphasias alongside neurotypicals during basic semantic and syntactic processing tasks, determining whether particular oscillations migrate as a function of a linguistic manipulation and whether they do so in ways which significantly differ between these groups.

Turning briefly to another area where traveling oscillations may provide novel insights, Gągol et al. (2018) discovered that *fluid intelligence* level (*gf*), or the ability to solve novel problems via abstract reasoning regardless of prior knowledge, depends on the precise synchronization of fast rhythms to the phase of slow rhythms. In particular, $\{\delta(\gamma)\}$ phase-amplitude coupling was found to be indicative of *gf* (more precisely, low γ at $\sim 36\text{Hz}$ and δ at $\sim 3\text{Hz}$), suggesting under the model in Murphy (2016a-c) that δ coordinates the extraction of various cortical representations (Chacko et al., 2018, also showed $\{\delta(\gamma)\}$ phase-amplitude coupling to be crucial for spatial attention). No *intervening* rhythms are involved in this form of phase-amplitude coupling, unlike in linguistic computa-

tion, which involves hierarchical structures and hence coupling between δ , θ , β and γ of differing combinations. Buzsáki et al. (2013) discuss that the propagation of low frequency oscillations across the cortex is considerably faster in the human brain than in the smaller rat brain, likely explaining the origins of *gf*. Mechanical morphogenesis – or “the process through which simple mechanical forces can lead to instabilities that [contribute] to the emergence of complex shapes” (Foubet et al., 2018, p. 3) – may also play a role in the development of complex neocortical organization.

Further, the close rhythmic similarities between the oscillatory basis of fluid intelligence and language processing support the notion that the computational basis of memory and certain language processes – *Load*, *Maintain*, *Spell-Out*, *Concatenate* and so forth – is shared (with the exception of labeling and cyclicity). Billeke et al. (2017) provide related evidence from EEG that the coupling of the amplitude of slow γ ripples (90–110Hz) to the phase of cortical δ differs as a function of cognitive task, ranging from memory recall to directed attention; supporting the role of δ - γ interactions in fluid intelligence. Meyer and Gumbert (2018) also performed an auditory EEG study utilizing uniformly distributed morphosyntactic violations across natural sentences, with their results providing evidence that the synchronization of electro-physiological responses at δ to speech implicitly aligns neural excitability with syntactic information.

Duncan (2013) discusses his frontoparietal *Multiple Demand System* and regards it as the basis of fluid intelligence, with this system more broadly implicating subcortical structures like the thalamus and basal ganglia. It seems to follow from this model and the findings in Gagol et al. (2018) that $\{\delta(\gamma)\}$ coupling ranges over this frontoparietal circuit, with the general processes of fluid intelligence possibly being enhanced by elementary forms of linguistic computation involving *Search* and *Concatenate* processes. While general forms of intelligence are coordinated by $\{\delta(\gamma)\}$ coupling, more complex, hierarchical syntax arrives only through a broader range of cross-frequency couplings. This likely explains why fluid intelligence is also at risk of impairment in the event of brain lesions, with either the paths of the traveling δ waves across the frontoparietal Multiple Demand circuit either being limited, or the cortical γ clusters they are typically coupled with being unable to synchronize.

Flanagan and Goswami (2018) also present evidence that changes in the magnitude of the phase synchronization index (Δ PSI) of slow amplitude modulations in the δ - θ range accompanies both phoneme deletion and plural elicitation – basic morphophonological tasks – suggesting that sensitivity to slow rhythms in speech forms a major aspect of morphophonological knowledge.

Other recent research points us in different, potentially fruitful directions. Headley and Paré (2017) conducted a large-scale review of the oscillatory memory literature in humans. In order to account for differences in oscillatory activity in memory-relevant regions during sleep (i.e., some forms of memory are sensitive to slow-wave sleep, others to rapid eye movement sleep), they suggest that while θ rhythms seem responsible for consolidating procedural memories during sleep, the literature indicates that δ rhythms during slow-wave sleep additionally promote the consolidation of declarative memories. Given the presently proposed role of δ in phrasal – and, hence, sentential and propositional – construction and interpretation, it is possible that during sleep the language system is active in this declarative consolidation process (though likely not causally, rather recruited in the service of processing efficiency), what with the crucial role of language in the generation of facts and certain events (see Cross et al., 2018, for a related approach, and whose oscillatory architecture for language is almost identical to that in Murphy, 2016a,b). The potential role of linguistic computations in declarative consolidation is easy to square with the well-known interactions between the hippocampus and cortical δ rhythms (Hahn et al., 2006). It would be of interest for future research to examine cross-frequency coupling during declarative consolidation to examine any potential similarities with language processing.

Another potential avenue for oscillatory theories of language is to implement logical operators like NOT, AND, NAND, XOR, NOT and Neg-AND. For instance, the first could be rooted in phase asynchrony. Merging/synchronizing two oscillations might implement an AND operation, an increase in amplitude of a long-range wave relative to the stable signature of a local traveling wave might serve to represent a NOT function, the rapid de-synchronization or phase-resetting of multiple waves could execute a NOR computation, and the annihilation of two oscillations might implement a XOR logic gate. Empirically, these hypotheses would

be readily falsifiable given the use of an experimental paradigm which permitted a careful execution of these basic semantic operations, such as in a setting where participants were tasked with implementing these operations over a range of auditory, linguistic and visual objects.

Lastly, according to Wexler's (1998) *Unique Checking Constraint* (UCC), a child's linguistic system is limited to checking only one syntactic property per linguistic environment. For instance, in the clausal domain AGREEMENT and Tense features cannot both be checked, and so only one is eliminated (producing the Optional Infinite stage of language acquisition). Since we are beginning to understand the oscillatory differences between child and adult language comprehension (Leong & Goswami, 2015), this constraint may be due to particular limitations on traveling θ oscillations across cortical areas responsible for coupling with γ pockets storing AGR-relevant and Tense-relevant features, with maturity likely providing the brain with a broader and more extensive traveling path. Recent work from Kurth et al. (2017) examined slow oscillations in sleep in a group of children ($n = 23$; 2–13 years) and showed that with increasing age, slow oscillations propagated across longer distances, with an average growth of 0.2 cm per year. The speed of the traveling waves remains unchanged across childhood, suggesting that the *interface* component of the equation in this chapter's title is subject to greater developmental changes than the core neural code for phrase structure building. Since this area of neurobiological research is a recent development, further studies of child language processing within these frameworks will be needed to elaborate on these hypotheses any further. The psycholinguistic possibilities of testing the morphology of traveling oscillations using MEG seem highly promising. An interesting question for future research concerns the relevance of traveling subcortical oscillations (e.g., parahippocampal migrations) and the morphology of traveling waves in nonhuman primates.

Dynamic studies of infant and child language processing will also be needed due to a current lack of understanding concerning the developmental characteristics of language-relevant brain rhythms. In one of the few studies exploring this topic, Schneider et al. (2016) revealed θ and β power decreases in adults at, respectively, left frontal and parietal regions and right parietal regions when participants processed ungrammatical sentences. These results were not replicated in children, despite simi-

lar abilities to detect ungrammatical constructions. The children instead displayed an N400 effect (a negative-going deflection peaking around 400 ms post-stimulus onset) at ungrammatical words while adults showed a greater P600 effect (a positive-going deflection peaking around 600 ms post-stimulus onset). Altogether, these results suggest that syntactic neurocomputational mechanisms go through various, dynamically marked developmental stages. Continuing this line of research, Leong et al. (2017) used EEG to show that infants not only entrain to the speech rhythm, but they appear better prepared for this than adults. Examining gaze directed speech in which an adult spoke to an infant, *partial directed coherence* (PDC) was computed for all pairwise connections at all EEG frequencies, with PDC being a directed measure of statistical causality (*how much does i predict j , independent of j 's history*). Leong et al. showed that phase coupling was weaker when the adult speaker shifted their gaze away during speech in θ , α and β (see also Schoch et al., 2017, who explore across-night dynamics of slow oscillations in children).

What is also needed is a more extensive investigation into the oscillatory activity of infants during complex thought, before they acquire language. Much of the language neural network is already in place (and left-lateralized) before birth (Dehaene-Lambertz, 2017), suggesting that exposure to speech is not necessary for the oscillatory basis of syntax to develop – intensifying further a central message presented here concerning the potential for a cluster of domain-general cellular and oscillatory codes to derive major components of linguistic computation.

A topic closely related to language development is the genetic basis of the oscillatory language system. This is currently an open field, but there at least seem to be clear directions available. One direction assumes that the oscillatory language system (called in previous work the *oscillome*; Murphy, 2016b) is largely genetically hard-wired. Murphy and Benítez-Burraco (2017b) provide a number of linking hypotheses between particular genes and oscillatory brain activity implicated in language, suggesting that much of the oscillome is likely genetically-directed; the set of genes implicated here is termed the *oscillogenome*. In contrast, another emerging direction is exemplified by Soloduchin and Shamir (2018). Weighing up whether the mechanisms responsible for generating and stabilizing oscillations are hard-wired or could be acquired via a learning process, they focus on the dynamics of spike timing depen-

dent plasticity and the effective coupling between two competing neuronal populations with reciprocal inhibitory connections, analyzing this via a phase-diagram of the model system that detects possible dynamic states of the network as a function of effective inhibitory couplings. They show that under a wide range of parameters, oscillatory activity can in fact emerge via an unsupervised learning process of spike timing dependent plasticity. It remains to be seen whether oscillatory activity does in fact emerge through such a learning process (since the fact that certain oscillatory features can do so does not necessitate the claim that all oscillatory features relevant to cognition emerge this way), or whether it is grounded in the genome.

4 CONCLUSION

In summary, linguistics can direct the brain sciences insofar as its insights into the universality of phrase structure building operations (or indeed rules of functional application in heuristic *Categorical Grammar*, or any number of other formulations of elementary combinatorics) inform the goals of neurobiology. The brain sciences can direct linguistics insofar as they place constraints on what possible operations neuronal assemblies and their oscillations can perform (see Badin et al., 2017, for an exploration of the notion of a neuronal assembly, which they see the defining feature of as being *one of dynamism*). While linguists should focus on making their claims about language biologically feasible, neuroscientists should conversely ensure they do not sideline the notion of computation, as stressed most forcefully by Gallistel and King (2009).

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