

AN OSCILLOMIC APPROACH TO THE HUMAN COGNITIVE PHENOTYPE: PHILOSOPHICAL AND EMPIRICAL REFLECTIONS

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Abstract

Exploring recent work in systems neuroscience and comparative biolinguistics, it is argued that only by decomposing the computational operations of language into their generic sub-operations will an explanatory neurolinguistics emerge. Methods of investigating the brain mechanisms of language comprehension are discussed, and the prospects for Dynamic Cognomics are explored alongside more fundamental considerations of top-down versus bottom-up studies of cognitive phylogenies. It is shown that the translational approach advocated by Dynamic Cognomics, promoting computational-oscillatory cross-talk, can establish a degree of alignment between core computational properties of the human cognitive phenotype (including the establishment of featural covariance) and a set of generic, domain-general neuronal mechanisms (including phase-amplitude coupling).

1. Introduction

It has been known since at least Wilson and Bower (1991: 498) that ‘the phase and frequency of cortical oscillations may reflect the coordination of general computational processes within and between cortical areas’. In Murphy (2015b), a model of linguistic computation was developed by embedding the syntactic sub-operations of the human computational system (the ‘cognome’; Poeppel 2012) within brain dynamics (the ‘dynome’; Kopell et al. 2014). This led to the formation of a research program termed Dynamic Cognomics, focusing on those aspects of brain dynamics specific to neural oscillations (the ‘oscillome’; Murphy 2016). But after the construction of a cognome-oscillome model through establishing significant isomorphisms between linguistic structure and oscillatory behaviour, there remained unaddressed tensions between the Darwinian thinking of descent, evo-devo perspectives on the organic form-function divide, and the generic computational properties of the language faculty. As a way of addressing these tensions, it is useful to first draw attention to the inadequacy of traditional linear cladograms, ‘according to which every seemingly new or more sophisticated feature of a cognitive mechanism, viewed as a novelty, is represented as a node on top of the old and shared elements’ (Boeckx & Theofanopoulou 2015). It was noted in Murphy (2015a) that the lack of non-human models for language has often been used to discourage biological inquiry into language, and that certain complex computational operations like *word movement* could have potentially remained dormant until the emergence of particular environmental pressures. But evolutionary homologies to language should not just be sought in the animal world, but also within the human brain. Drawing up linking hypotheses between linguistics and neuroscience should pressurise linguists into formulating their syntactic, semantic and phonological models in such a way as to allow for implementation in the wet-ware of the brain.

A general defence of a highly interdisciplinary comparative biolinguistics was made by Hall (2012), who noted that a biolinguistic approach to phonology would lead to an expansion of the concerns of phonologists (embracing particular aspects of biology), but would also simultaneously lead to a narrowing of other particular concerns, since ‘If some of phonology is really syntax, and some of it is really phonetics, then relatively little of phonology is phonology’. The point is well directed: By translating linguistic theory into non-syntactic terms

(that is, neurobiological and biophysical terms), notions such as *language* and *set-formation* can be re-situated and potentially given a biologically plausible level of explanation. A program such as Dynamic Cognomics (Murphy 2015b), suggesting ways of investigating language from multiple perspectives (cognome, dynome, connectome, genome) will satisfy a greater number of theoretical and empirical demands. The range of available biophysical discussion has by now expanded sufficiently to permit the construction of a science of language which can exploit the full interdisciplinary range seen in the cognitive, biological and natural sciences.

2. Philosophical Considerations

A notable justification for an interdisciplinary study of language is found in Miłkowski's (2012: 81) assessment of the limits of computational explanations of cognition, which notes that 'Some really basic cognitive systems, such as sponges or plants, may be explained in terms of simpler computation models, whereas more complex processes require interlevel explanations to give meaningful, idealized explanations and predictions'. The biological study of language should be concerned with presenting generic computational operations that, in Poeppel's (2012: 52) words, 'could be implemented quite straightforwardly in neural circuits'. There are doubtless certain domains which have regularly exploited the findings of modern neuroscience and, more often, quantum physics and other fields; in particular, certain strands of psychology and neo-spiritualism (see Burnett, 2016 for the pitfalls of 'neuro-nonsense'). Care must be taken, then, to decompose the language faculty into the kinds of constituent computational parts which could be deemed neurobiologically plausible. The right level of granularity must be sought after at all levels of biological and cognitive analysis. What is not often recognised, though, is that linguists approaching the biology of language who keep to discussions of *syntax* and *semantics* do so from purely atheoretical grounds (although see Zaccarella et al. 2015 for a careful imaging study of Merge versus word lists, with the former implicating the pars opercularis and superior temporal sulcus). There is nothing in the principles of theta-role assignment, agreement relations or evolutionary developmental biology which prohibits the formation of multidisciplinary perspectives on language evolution and comprehension. Just as classical concepts like *mind* and *motion* are now understood to be too coarse-grained and vague to be of any empirical use, so too should linguists begin to see *labels* and *movement* as inadequate to the task of constructing cognitive phylogenies.

Throughout the twentieth century, artificial intelligence research repeatedly moved in and out of synch with the biological sciences. In comparison, linguists have often claimed to be in synch with biology, but have provided little direct evidence to back these claims up. Somewhat peculiarly, it was only fairly recently that the brain was considered eligible to be the focus of biolinguistic inquiry. Concurrently, when biolinguistic investigations do get off the ground, the focus of investigation is often left unclear. Matsunaga and Okanoya (2014), for instance, discuss what they call 'potential regulators in the faculty of language', a superfamily of proteins (cadherins) identified as cell adhesion molecules and which may play a role in vocal behaviour. This biolinguistic perspective is to be welcomed, but the target of this discovery is the sensorimotor faculty, not the syntactic faculty.

Relatedly, the concept of third factors in theoretical linguistics, referring to principles not specific to language which influence its design (Chomsky 2005, Narita 2014), is often ridiculed for being 'vague', as if it supposedly constitutes a uniform neurobiological mechanism. Similarly, in 1734 Bishop Berkeley criticised the intuitive notion of infinitesimals as 'Ghosts of departed Quantities' (1992: 199), and it wasn't until 1966 that Abraham Robinson provided a firm mathematical foundation for them in Non-Standard Analysis. This alone should

encourage us not to rule out a forthcoming formulation of specific third factor constraints within the domain of, for instance, molecular biology or neurobiology (see Johansson 2013 for an insightful critical review of the third factor literature and its goals and limitations). Neural oscillations may well be what is needed to explain the minimal search principles of labeling; departing from the neo-Darwinian adaptationism of Schoenemann's (2012) neurolinguists.

On the issue of computational efficiency, and considering the above multidisciplinary demands, it may also be useful to distinguish between laws of physics and laws of nature. The former are found in the physical sciences, such as Newton's laws of motion, while the latter are underlying principles which have parametric application via distinct mechanisms (e.g. neural, entomological) across various domains ranging from insect navigation to subatomic particles. Likely candidates for natural laws include least effort (Zipf 1965/1949) and last resort principles (Narita 2014), implemented within the context of a specific explanatory theory (linguistics, neurophysiology, chemistry, etc.). The labeling operation in syntax utilises notions of least effort, a law of nature, but would not apply to the motion of planetary bodies, which would implement such notions through different mechanisms. Similarly, brain rhythms are a manifestation of a natural law of 'periodicity' (the term used in the earth sciences) or 'oscillation' (physics) or 'cyclicality' (engineering and linguistics), which all refer to the steady recurrence of a particular theoretical structure (see Tass 1999 for a discussion of dynamic synchronisation in physics which may be responsible for the oscillations of the dynamo, in a similar way that oscillometric operations may be responsible for the cyclicality of the cogno; see also Rodrigueus et al. 2016). The neural mechanisms which construct the human computational system are likely not unique to language, being instead domain-general and operative in other cognitive faculties (see the hierarchical processing found in vision (Ursini 2011) and motor planning (Fujita 2009)), and indeed other species (Schlenker et al. 2014). Higher cognitive functions implicated in γ , for instance, have their origin in 'a limited set of circuit motifs which are found universally across species and brain structures' (Bosman et al. 2014: 1982). These considerations have direct theoretical and experimental implications for linguistics, neuroscience and anthropogeny. The operations of syntax are not to be found in any particular anatomical region, but may rather emerge from the way brain waves synchronise the activation of pathways storing discrete featural representations (though how this information is stored is a separate issue). While it could be said that this simply amounts to a special kind of localisation, understanding brain rhythms could on the contrary shed light on why language is restricted to its particular computational properties, and not some other imaginable operations which fall outside neurophysiological constraints.

3. Empirical Considerations

Turning to more empirical considerations, the phonological representations explored in Giraud and Poeppel's (2012) dynamical model of the human auditory system crucially rely on perceptual events. Syntactic representations, in contrast, are internally self-generated. Unless this is taken into consideration, neurolinguists may well be confined to studying only the products and epiphenomena of narrow syntax. Nevertheless, if γ waves, for instance, reflect a fundamental unit of linguistic interpretation, as proposed in Murphy (2015b), then analysing the time course of γ embedded within slower rhythms would likely be a fruitful direction for experimental research in humans, even if the semantic content manipulated by such rhythms remains 'invisible' – as, indeed, it may remain, given our cognitive 'scope and limits' (Russell 1948), 'bounds of sense' (Strawson 1966) and other such constraints (see also Buzsáki 2010).

An answer to what Embick and Poeppel (2015: 363) term the second specialisation question was presented in Murphy (2015a): ‘Are there particular parts of the [computational-representational] theory that are more likely to be candidates for explanatory neurolinguistic explanation than others?’ Labeling and cyclic transfer were suggested as candidates. These are the operations which attribute to a given set a syntactic identity and maintain it in memory whilst transferring these structures to the conceptual and sensorimotor interfaces in ‘chunks’ of a given size. But what about the opposite problem of neurobiological specificity? This is posed by the first specialisation question: ‘Are there particular levels of [neurobiological] organisation that are to be privileged as candidates for [computational-representational] specialisation?’ In Murphy (2015b), it was suggested that brain dynamics, in particular neural oscillations, are likely candidates to be privileged in such a way. Embick and Poeppel (2015) also make a useful distinction between *correlational*, *integrated* and *explanatory* neurolinguistics. The first occurs when neurobiological (NB) computation is correlated with a computational/representational (CR) theory, the second when NB data provides a way of selecting between CR theories, and the third when properties of NB explain why a CR theory is the way it is. As the authors explain, ‘although cognitive theories and NB theories are advancing in their own terms, there are few (if any) substantive linking hypotheses connecting these domains’ (Embick & Poeppel 2015: 357). The ‘translation’ project begun in Murphy (2015b) – converting parts of the cognome into the oscillome – is only one step towards explanatory neurolinguistics, concerned as it is primarily with *correlational* investigations (Embick & Poeppel 2015). It is worth noting in this connection that due to the frequent overlap in roles attributed to β and α waves, Bressler and Richter (2015: 63) argue for a re-definition of neural oscillations based on functionality, not arbitrary clinical and frequency boundaries. Though this does not currently warrant a re-formulation of any oscillomic proposals, it is worth keeping this approach in mind, as a re-conceptualisation of the cognome may well simultaneously require a re-formulation of the oscillome.

Though the approach to Dynamic Cognomics outlined in Murphy (2015b) was informed by a top-down translation-based methodology, bottom-up oscillomic investigations, which attempt to re-construct the cognome based on present neurobiological understanding, are more in line with Darwinian thinking of modification by descent. Top-down perspectives can be highly instructive up until the point that sufficiently decomposed and generic operations and processes have been discovered. But insisting on a wholly top-down perspective is inconsistent with both Darwinian and Thompsonian thinking (see Balari & Lorenzo 2013). The goal should be to unite, and not divide, information from different computational and implementational levels through generic brain rhythm mechanisms. As explored by Balari and Lorenzo (2015), evolution ‘tinkers’ existing mechanisms (e.g. slight changes in oscillomic operations like selective inhibition via lower-level connectome-based modifications) to yield novel higher-level operations like ‘Form Set’. Richer collaboration between linguists and systems neuroscientists, computer scientists and geneticists consequently needs to take place, developing an understanding of how the ‘order’ of computationally efficient linguistic sub-operations arises out of the ‘chaos’ of brain dynamics. For instance, the glymphatic system (responsible for ‘cleaning’ the brain of protein aggregates) is also responsible for delivering glucose to neurons, and possibly also to white matter (Jessen et al. 2015). Its potential role in brain function, and consequently cognition, is only just beginning to be researched. Other recent work has shown that electrical signalling is present in bacterial communication (Prindle et al. 2015), suggesting with fascinating and timely clarity that the oscillatory properties of the language-ready brain arise from ancient, generic mechanisms.

The experimental obstacles towards a comprehensive dynamic account of language are numerous, imposing serious limits on investigation. Most notably, speech contains no markers for the hierarchical structure of language, and so some measure of internal markers needs to be employed instead. Nevertheless, some progress has been made in researching isomorphisms between linguistic structure and oscillations. Addressing the possibility that oscillations can provide such an empirical measure on linguistic structure building, Ding et al.'s (2016) MEG study demonstrated that during listening to connected speech cortical activity of distinct rhythms corresponded to the time course of (standardly hypothesised) linguistic structures like words and phrases. Particular rhythms became entrained to linguistic structures of distinct levels, with 'entrainment' referring to the process of oscillations becoming synchronized with temporal regularities in an external input streams. Cortical dynamics consequently emerge at all linguistically relevant timescales. To show this, Ding et al. constructed stimuli in which constituent structure was dissociated from prosodic and statistical cues, ensuring that only grammar-internal processes were engaged in the construction of linguistic structures, without the assistance of other mechanisms. The response rhythm spectrum revealed distinct peaks at syllabic, phrasal and sentential rates. These were, respectively, 4, 2 and 1Hz frequencies. This suggests a major role of δ and θ rhythms in all levels of linguistic computation. To quote Ding et al., 'coherent synchronization to the correlated linguistic structures in different representational networks, for example, syntactic, semantic and phonological, provides a way to integrate multi-dimensional linguistic representations into a coherent language percept'. To show that these cortical dynamics reflected syntactic structure building, Ding et al. eliminated phrasal and sentential structure by also including random syllable sequences. When these were presented to subjects, only acoustic level tracking occurred, lending support to the neurobiological (and not just psychological) validity of abstract linguistic structure. This design could in future be used to achieve a finer-grained picture of what the brain regards as phrasal and sentential, challenging or supporting particular computational theories of phrase-structure building (e.g. labeling theory and the numerous views on cyclic transfer).

In what follows, I will assume familiarity with the oscillomic model proposed in Murphy (2015b, 2016). Given the syntactic labeling role (i.e. maintaining a phrase in memory and attributing it a syntactic identity) attributed to β , it may be that this slower rhythm couples with and determines the phase of embedded γ cycles responsible for storing conceptual 'roots', thereby 'labeling' the faster rhythms by attributing to them a grammatical property (i.e. phasal features) and maintaining them in memory for the next derivational cycle. This may contribute to the slower rhythms (1-4Hz) documented by Ding et al.'s (2016) study of basic phrase structures, which they detected at language-relevant cortical structures like the left inferior frontal gyrus and the posterior and middle superior temporal gyrus (although Ding et al.'s finding of increased δ for real words compared to pseudo-words was not replicated in Mai et al.'s (2016) study, and so further work is needed to clarify the dynamics of semantic memory). β also plays a crucial role in sensory prediction through being modulated by unpredicted pitch stimuli 200-300ms post-onset (Chang et al. 2016), and it is conceivable that a domain-general updating procedure is carried out by ensembles oscillating in this range, with both perception and language requiring perceptual and structural property updates (see Palmer et al. 2016 for further evidence that β power reflects sensorimotor uncertainty estimates). Abel et al. (2016) also detected robust and focal β increases at the left and right anterior temporal lobe during the retrieval of names for people and tools.

Vignali et al.'s (2016) study of self-paced sentence-level processing (using naturalistic, ecologically valid fixation-related potentials, in contrast to most electrophysiological work on sentence processing which relies on serial visual presentations) revealed that semantically

incongruous words elicited a decreased β response relative to congruous words, while γ power increased linearly as sentences proceeded. Interestingly, they also found θ power increases in the 300-900ms time window after the onset of syntactically correct sentences but not after the onset of randomised word lists, suggesting that this slower rhythm plays a role in cyclic Spell-Out operations and the retrieval of lexical representations. Other recent research point to a role for θ in synchronising ‘hearing’ and ‘speaking’ information in left auditory-related cortex and Broca’s area, with Elmer and Kühnis’s (2016) EEG study of simultaneous interpreters (individuals who are trained in translating a source language into a target language virtually simultaneously) revealing increased θ power and synchronisation during a semantic decision task relative to controls. Given the role of hippocampal θ in working memory processes (Murphy 2016), it is also likely that this region, along with subcortical θ - and α -oscillating regions like the thalamus, contribute to the rapid lexical access abilities of simultaneous interpreters. Burgaleta et al.’s (2016) study of bilingual brains revealed significantly expanded subcortical structures relative to monolinguals, localised in bilateral putamen, thalamus, left globus pallidus and right caudate nucleus, pointing to an important role of these regions in language (see also Henderson et al. 2016 for evidence of a distributed network responsible for syntactic prediction, spanning bilateral inferior frontal gyrus and insula, and fusiform and right lingual gyri). Matchin and Hickok (2016) provided further evidence against the classical Broca-Wernicke model of neurolinguistics, with syntactic perturbation (involving the cued, mid-utterance restructuring of the planned syntax of a sentence) being shown to not involve Broca’s area or the anterior temporal lobe, but rather a cortical-subcortical network involving the right inferior frontal gyrus (Lam et al. 2016 also provides an oscillation-based rejection of the classical Broca-Wernicke model). In short, while a framework for how neural oscillations contribute to sensory perception is beginning to emerge (see Obleser 2016 for discussion), the prospects for cognitive oscillatory frameworks are also advancing apace.

The oscillomic model in Murphy (2016) also permits an empirical exploration of a number of topics classically isolated to computational/representational debates. For instance, Abe (2016) claims that syntactic movement is a composite of Copy and Merge, and that copying a syntactic object makes the original inactive during syntactic computation. In oscillomic terms, a number of hypotheses could be entertained about how such processes are implemented. A separate (neuroethological) question then surfaces regarding how items are held in short-term memory before being discarded from the workspace. Since other recent work suggests that a number of syntactic problems (the Halting Problem, the Empty Category Principle and Extended Projection Principle) can be explained by the proposal that moved syntactic objects remain in positions where their unvalued features can be valued (Hosono 2016), this affords a central role to the oscillatory synchronisation processes claimed in Murphy (2015b, 2016) to be responsible for featural covariation/agreement. Taking into consideration much of the working memory oscillation literature (Lundqvist et al. 2016, for instance, show that working memory information is linked to brief γ bursts while β bursting reflects a default network state interrupted by γ), it was suggested in Murphy (2016) that features are valued by distinct ensembles being phase-locked, ‘agreeing’ in both rhythmic and representational senses.

These proposals are in line with Mai et al.’s (2016) finding of γ -related modulations during semantic and syntactic processing. A general computational operation (feature valuation) can therefore approach a degree of alignment with a general oscillatory mechanism (cross-frequency coupling). The question of whether these computations are achieved through increasing or decreasing phase-amplitude coupling is of course an open one, and should not be assumed *a priori*, with distinct cognitive systems likely employing oscillomic processes in different ways: Esghaei et al. (2015), for instance, show visual attention in macaque monkeys

decreases phase-amplitude coupling, seemingly to increase neuronal discriminability for attended stimuli. Visual cortex appears to use phase-amplitude coupling to regulate inter-neuronal correlations and enhance the discrimination of visual stimuli, selecting the appropriate representations. Relatedly, Mai et al. (2016) found decreased θ - γ cross-frequency coupling for speech relative to non-speech, along with increased θ power for speech and increased γ power for real-words relative to pseudo-words (as predicted by the oscillomic model in Murphy 2016). They suggest that the reasons for decreased cross-frequency coupling in speech is due to the higher difficulty of sound matching in non-speech sounds which result in higher psychoacoustic working memory demands, yet their findings may also be due to a similar neuronal discrimination process as the one proposed by Esghaei et al. (2015). Phase-amplitude coupling increases (as in a number of studies reviewed in Murphy 2015b) and decreases (as in Esghaei et al. 2015) consequently play a number of distinct functional roles, although the underlying physiological mechanisms which give rise to them are still not well understood (see also Asano & Gotman 2016 for the emerging potential of electrocorticography (ECoG) to monitor the oscillatory dynamics of language).

4. Conclusion

As the empirical and theoretical considerations discussed above suggest, Dynamic Cognomics has the potential to achieve what Poeppel (2012: 35) terms ‘theoretically well-motivated, computationally explicit, and biologically realistic characterizations of function’. I take this approach to be part of a line of research starting with Lisman and Idiart’s (1995: 1512) seminal suggestion that ‘brain oscillations are a timing mechanism for controlling the serial processing of short-term memories’. With the emergence of this program, there is no longer a coherent notion of ‘language’ or ‘labeling’ or ‘syntax’. There is only the brain, with its various cell assemblies, electrophysiological properties, and mechanisms of phase-locking, cycle skipping, and other oscillomic operations. The explanatory reach of these operations still remains fairly modest, but experimental advances in tandem with developments in theoretical neurobiology along the lines I have suggested may well prove conducive to grounding linguistic computation in the brain.

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