



# Commentary: A Compositional Neural Architecture for Language

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## A Commentary on

### A Compositional Neural Architecture for Language

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Martin (2020) defends a model of linguistic computation relying on gain modulation. I will argue that any gain modulation model of language faces a number of internal conceptual and empirical difficulties, and that our current understanding of gain modulation does not support its use as a core component of linguistic computation.

## THE PROPOSAL

Martin (2020) defends a multidimensional coordinate system for language based on neurophysiological models of sensory processing. With ambitious scope, Martin aims to connect theories of processing and neural implementation, an extraordinarily challenging undertaking. Martin maintains that neural trajectories (of these coordinates) encode *sensory*, *motor*, and *abstract linguistic states*. Gain modulation tunes the path of these trajectories in accordance with behavior. Martin claims that increasingly abstract linguistic structures (from syllables to morphemes to words) are inferred via gain modulation which she defines as “the way neurons combine information from two or more sources.”

Martin (2020) reports how gain modulation underlies “coordinate transform between sensory modalities and between sensory and motor systems.” She cites classic work on cellular dynamics (Salinas and Abbott, 2001), but does not cite other work (e.g., Dayan and Abbott, 2001) where the limitations of gain modulation are stressed, e.g., gaze-dependent gain modulation of retinotopic visual receptive fields is well-reported, but the relevance of gain modulation to higher cognition is not established [(Dayan and Abbott, 2001), p. 17].

Martin (2020) makes an additional claim that “gain modulation also offers a built-in system for predictive coding,” citing Friston (2005); more recent, updated accounts (e.g., Friston, 2018) rely on an interplay of a range of other processes. Moreover, Friston’s ventures into language (i.e., Friston et al., 2017) rely on other neural mechanisms (belief propagation in neuronal process theories, phase precession, theta-gamma coupling) employing distinct softmax functions, logarithmic transforms, and linear algebra (implemented via firing rate functions, non-linear postsynaptic responses, and neuronal connectivity, respectively).

Potential advantages of Martin’s model are the multiple-realizability of gain modulation and the fact that her model relies on simple changes to a highly conserved, generic neural process—an elegant framework for language evolution.

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## A REASSESSMENT

Ferguson and Cardin (2020) provide a comprehensive review of gain modulation, pointing to a common set of mechanisms: GABAergic inhibition, synaptically driven fluctuations in membrane potential, and changes in cellular conductance. Ferguson and Cardin (2020) note that diverse cortical functions such as information integration across cognitive, sensory, and motor systems seem to be performed through gain modulation. Further, regulation of neural gain can provide “an integration mechanism whereby information from multiple sources can be non-linearly combined via multiplicative modulation of the cell’s response to inputs” [Ferguson and Cardin, 2020, p. 81]. Martin (2020) defends an additive, rather than a tensor-based multiplicative, formulation of linguistic compositionality. Ferguson and Cardin (2020) review how visual properties that must be *decoded separately* in higher-order areas of non-human primate visual cortex are combined multiplicatively (e.g., object identity), whereas parts that must be *integrated* (e.g., object sub-parts) are combined additively. It may be that additive-only models can capture integrative language functions, but that structural (hence, syntactic) separation may require multiplicative modulation.

Ferguson and Cardin (2020, p. 88) note that gain modulation may be able to *increase information transmission* and provide *computational efficiency* within a given network. Nevertheless, it remains unknown how gain modulation at the single-cell level contributes to population coding that can be read out by downstream targets. The authors conclude that “gain is regulated by a wide range of influences, including attention, learning, locomotion” [(Ferguson and Cardin, 2020), p. 89]. While the role of gain modulation in sensory-to-motor conversions is well-established (evidence that left premotor regions are implicated in language comprehension can be found in Keitel et al., 2018; see also Molinaro and Lizarazu, 2018; Woolnough et al., 2019; Poeppel and Assaneo, 2020), and information transfer between motor and higher-order cortical structures has been shown [crucially via cross-frequency coupling; (Keitel et al., 2018)], gain modulation has not been implicated in higher-order aspects of language in non-motor regions (i.e., components of the cortical language network). As such, it seems premature to use gain modulation as a core component of higher-level linguistic computation.

Ferguson and Cardin (2020, p. 89) also note that “the precise relationship between gain modulation of single neurons and the encoding and transmission of information at the population

level is not well-understood,” and that “the reliability and repeatability of gain modulation of single neurons and cortical networks is unknown.” Given this, it seems not well-motivated to stipulate a close connection between gain modulation and oscillatory activity in language. Since gain modulation appears relevant to enabling networks of neurons to produce distributed representations of stimulus features (as opposed to generating inferences to higher abstract structures from such features), it may be that gain modulation goes the way of entrainment: Initially viewed as a crucial mechanism for all manner of linguistic processes (from syllables to sentences) before being relegated by some to a role in (possibly higher-order) speech perception (Keitel et al., 2018; Meyer et al., 2019; Murphy, 2020).

Advancing on and moving away from previous theoretical assumptions (Martin, 2016), Martin (2020) now proposes that cortical oscillations structure speech input into linguistic representations via gain-modulated multiplexing. Multiplexing models of language have been proposed elsewhere, and it is unclear how (Martin, 2020) *gain-modulated multiplexing* is a step forward. For instance, a range of papers (Murphy, 2015, 2016, 2018, 2020; Murphy and Benítez-Burraco, 2017; Benítez-Burraco and Murphy, 2019) utilize multiplexing as operationalized via cross-frequency coupling, and there is ample empirical support for the involvement of this mechanism in aspects of language processing beyond semantic compositionality, such as prediction and syntactic categorization (see Murphy, 2020 and references therein). In addition, testing the claims in Martin (2020) will require a deeper understanding of the relationship between gain modulation and processes that we can more easily record in the human brain. Lastly, while Martin (2020) presents a list of non-specific predictions pertaining to “low frequency power” increases during “structure” building (an eventuality which would not exclusively support a gain modulation model), Murphy (2020) presents specific predictions about distinct low frequency band increases, suppressions, and coupling dynamics, and can hence be evaluated more clearly.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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**Conflict of Interest:** The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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