Short communication

Neuroemergentism: Levels and constraints

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A B S T R A C T

Everywhere in Nature, patterns emerge when the combination of parts on a lower level creates more complex structures which are then subject to constraints and competition on this new level. This means that emergentist accounts must focus on a description of levels, competition, and constraints.

The four approaches to neuroemergentism analyzed by Hernandez all recognize the role of emergent levels and new constraints. Together, they can be used to further articulate a fuller theory of neuroemergence.

Nature abounds with emergent processes. Whether we are talking about the shape and properties of water, soap bubbles, ocean tides, honeycomb cells, protein molecules, optical dominance columns, mental representations, neurolinguistic modules, linguistic forms, or social groups, we can view all structures in the natural world as emerging from the force of constraints on different levels. The question is not whether these patterns and structures are emergent, but rather what might be the mechanisms that determine the shape of the emergent patterns. Everywhere in Nature, patterns emerge when the combination of parts on a lower level creates more complex structures which are then subject to constraints and competition on this new level. This means that emergentist accounts must focus on a description of levels, competition, and constraints (MacWhinney, 2014).

As Mill (1859) noted, water provides a perfect example. To produce water from hydrogen and oxygen, one must apply a spark of energy to break the covalent bonds. After that, the process of molecular formation produces its own energy and the reaction will go to completion. The first emergent property of this new molecule is its polarity, which then responds to constraints on the molecular level to produce hydrogen-bonding of each water molecule with up to four additional water molecules. These new links then produce water's high surface tension as a further emergent property, as well as its high thermal conductivity, specific heat capacity, heat of vaporization, and heat of fusion. As water accumulates in larger bodies like lakes and oceans, these further emergent properties shape new emergent patterns such as snowflakes, rain drops, ocean currents, glaciers, thunderstorms, and many other features of our planet and its climate.

This interplay of structures, combinations, levels, and constraints works out in remarkably similar ways in the brain. During embryogenesis and epigenesis patterns in the mRNA serve as a template for the formation of new proteins. The process of protein folding goes through four levels of structure and constraints to determine the final folded form. On the primary level, a simple chain of amino acids emerges from the ribosome. On the secondary level, hydrogen bonding serves to create either helices or pleated sheets, based on the nature of the sequences of amino acids from the primary level. On the tertiary level, the helices and pleated sheets twist into other forms based on hydrophobic and hydrophilic attractions. On the quaternary level, multiple polypeptide chains formed on the teriary level combine further to produce still more complex 3-D patterns appropriate for the functioning of particular proteins, such as the ability of hemoglobin in transport oxygen, or the ability of antibodies to engulf viruses. On each of these four levels, folding is further guided by catalysts and molecular chaperones. Once proteins are available for neuronal functioning, they can further determine the structure of neurons, transmitters, and hormones. As neurons group on higher levels, they are subject to

constraints from neuronal packing, local and distal connectivity patterns, activation thresholds, gang effects, and other properties of neural assemblies and areas.

When we seek to elaborate neuroemergentism, it is not enough to confine our accounts to levels, combination, and constraints. We also need to consider the process frames and timescales involved in specific neural processes. This means that we need to recognize specific emergent levels and the nature of the constraints operative on those levels. MacWhinney (2015) groups the many processes that shape human language into five rough classes: genetic, ontogenetic/epigenetic, consolidation, processing, and social. The slowest moving of these processes are those that operate on the timescale of population genetics. Here, we can talk about things such as the emergence across hominid evolution of an increased reliance on mirror neurons (Arbib, 2015), adaptations of the vocal tract for speech, and control of synaptogenesis in motor neurons through modifications of FoxP2 (Fisher & Scharff, 2009). The expression of these fundamental evolutionary changes occurs during epigenesis, which can vary in terms of its canalization in the phenotype (West-Eberhard, 2003). The degree to which cortical areas involved in language either lose or retain their plasticity can then be further shaped by both experience and gene regulation during ontogenesis or epigenesis (Werker & Hensch, 2014). A still faster moving set of processes involves the consolidation of new linguistic skills and representations through interactions of the hippocampus and the basal ganglia with the cortex, during both language use and sleep. In some cases, these processes can lead to new representation after even one exposure, whereas other, more abstract patterns may require days and weeks for full consolidation (Honey, Newman, & Schapiro, 2017).

Neuronal reuse and recycling are subject to constraints operative on the process/time scales of epigenesis and consolidation. For example, neuroemergentism views the exaptation of the left FFA to serve as the VWFA as an illustration of reuse of an old form for a new function. As Dehaene and Cohen (2007) and Hernandez et al. (2018) note, this type of recycling depends both on the cytoarchitectonic structure of an area and its pattern of connectivity with other areas involved in a type of processing. In the case of learning to read, the ability of the left FFA to encode precise visual patterns, along with its connectivity to the ventral stream of language processing (Hickok & Poeppel, 2004) allow it to take over the function of visual word processing.

Dehaene's theory of neuronal recycling (Dehaene & Cohen, 2007) is highly compatible with Anderson's theory of neural reuse (Anderson, 2010). If an area can serve multiple functions in alternative configurations of functional neural circuits, then recycling can be directly supported during ontogenesis. The theory of neural reuse can also be articulated in terms of the concepts of levels and constraints to the degree that particular functional circuits serve to instantiate specific levels of processing and consolidation, such as lexical activation, syntactic combination, reading, or memory for prose.

In addition, the developmental changes envisioned by both neuronal recycling and neural reuse often obey non-linear dynamics, as argued by the proponents of neuroconstructivism. Developments on a given level often depend heavily on the establishment of preexisting conditions on other levels. For example, the differentiation of the tissues of the eye in the human embryo depends on inductive forces deriving from its original location next to the heart. Similarly, the early development of imprinting in precocial fowl and attachment in human children depend on the timing of availability of visual capabilities for accurate face recognition. This means that neuroemergentism must provide an account that tracks the appearance of new levels through developmental time, just as Biology accounts for protein folding across four levels emerging in a much shorter developmental time.

Recycling and exaptation involve related processes operating across contrasting timescales. Exaptation involves the emergence of new structures across an evolutionary timescale, whereas recycling involves the emergence of new structures across an ontogenetic or epigenetic timescale. Dehaene cites the emergence of feathers in dinosaurs as involving the exaptation of scales for thermogenesis and sexual display. As West-Eberhard (2003) emphasizes, it is the phenotype that is the locus of evolution. Phenotypic variations arise from complex processes during ontogenesis, including niche changes, sexual dimorphism, the Baldwin effect, and gene expression, as well as recycling and reuse. When they are competitively successful, recycling and reuse during the lifetime of individuals is linked to structural variations that then diffuse to the overall gene pool, producing exaptation in the species. In human evolution, individuals who were able to make greater use of gesture, gaze contact, referencing, and cooperative behaviors gained a reproductive advantage, leading eventually to exaptation of these skills as supports for the emergence of spoken language.

Hernandez et al. question whether exaptational processes, as formulated by Dehaene, would be sufficient to account for major evolutionary shifts in human cognition without relying more clearly on non-linear dynamical processes. He points out that small changes in basic systems may lead to big consequences. One idea that is very much in line with this is the emphasis that Hauser, Chomsky, and Fitch (2002) placed on the emergence of recursion as the determinant of unique features of human language, and possibly cognition more generally (Mithen, 1996). This idea certainly fits in well with the overall emphasis in emergentism on structural determination through emergent levels. After all, if the mere combination of two hydrogen atoms with one oxygen atom can lead to such profound consequences for the climate of our planet, it could be that the emergence of recursion could have a similar effect for language, thought, and culture. However, there are many alternative emergentist scenarios for these developments (MacWhinney, 2005), as well as good reasons to doubt that recursion alone has had this type of impact (Everett, 2015). Although it is difficult to falsify emergentism, it is certainly possible to falsify particular emergentist accounts.

The fastest moving language processes are those involving online conversational processing. When we start to speak, all the structures that have been shaped through genetics, epigenetics, and consolidation come into play in a highly competitive (but also cooperative) fashion. As Hernandez et al. point out, bilingual processing shows us how the intense competition between two languages can be resolved through the growth of higher levels of attentional control. This control allows bilinguals to shift between languages in different contexts or within a single conversation through code-switching. A fully explanatory neuroemergentist account of code-switching will need to explain how conversations, utterances, words, and sounds are formed in each of a bilingual's languages and then interleaved during online processing. In code-switching, the choice of a given language at a particular moment in time can be influenced by fast-moving processes such as the speed of lexical access or pressures from surrounding syntactic frames, as well as

slow-moving processes such as the need to express solidarity with a particular language community. In order to understand the emergence of these complex structures during processing, we need to consider how all of these many sources of information are integrated smoothly online. Speakers with language disorders such as stuttering, aphasia, dementia, or Specific Language Impairment, as well as learners of a second language, may encounter particular problems achieving the type of smooth neuronal processing integration required for full fluency. Studies of these problems can help us understand the ways in which genetics, epigenetics, ontogenesis, consolidation, and processing interact at the moment of speaking. The process of online information integration can depend on the mechanisms of summed activation characterized in neural network models along with processes that allow decisions to cross over gates and thresholds (Ratcliff, Smith, Brown, & McKoon, 2016) to allow the ontime arrival of information from diverse areas of the brain. Studies of speech errors in normal speakers can reveal some of the forces that can put stresses on this system.

Christiansen and Chater (2008) (C&C) argue that language is shaped by the brain. They view language structure as arising from earlier structures, much as protein structures arise from an underlying substrate of polypeptide chains. They list a variety of cognitive, perceptuo-motor, learning, and pragmatic constraints that determine various aspects of language form. Their analysis echoes the earlier formulation from MacWhinney, Bates, and Kliegl (1984) that "the forms of natural languages are created, governed, constrained, acquired and used in the service of communicative functions." However, C&C's formulation of neuroemergentism extends this analysis by noting that communicative functions must be processed through the brain. Moreover, C&C propose several core constraints linked to levels of language processing. They note that comprehension is constrained by incrementalism (O'Grady, 2015), that articulatory phonology is constrained by the shape of the vocal apparatus, that pattern learning is constrained by mechanisms in Broca's area, that patterns of anaphora are constrained by pragmatic preemption, and that the emergence of consistent word orders in language facilitates learning and consolidation. Their view of language as shaped by the brain is fundamentally compatible with neuroemergentism, as well as with the ongoing emphasis within functional linguistics on language as emerging from multiple competing constraints (MacWhinney, Malchukov, & Moravcsik, 2014).

Hernandez et al. demonstrate that these four approaches to neuroemergentism are in fact highly mutually compatible. The analysis I have given above further supports his conclusion inasmuch as each perspective views language form as arising from combinations of items on new levels with new constraints through the development of the species and the individual. The compatibility of these approaches should give us cause for optimism, allowing us to focus on the core tasks of identifying the specific levels, constraints, competitions, timeframes, and processes involved in shaping human language.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jneuroling.2018.04.002.

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