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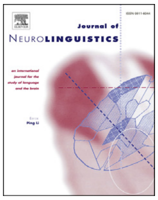

Perspective

# A conjecture about the neural basis of recursion in light of descent with modification

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A R T I C L E I N F O

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A B S T R A C T

The goal of this paper is to examine the possible neurobiological basis of a defining property of the human language faculty: recursion. I suggest that recursion should be understood in light of Darwinian's descent with modification. Descent: that is, based on ingredients of neural circuitry found in 'non-linguistic' species; and modification: a reconfiguration that is specific to anatomically modern humans. I argue that the expansion of the parietal region associated with the globularization of the neurocranium in our species contributed to the transformation of the connection between Broca's and Wernicke's region via Geschwind's territory, and enabled the pairing of evolutionary ancient networks that together became capable of constructing and processing not just sequences, but sequences of sequences.

## 1. Introduction

The goal of this paper is to examine the possible neurobiological basis of a defining property of the human language faculty: recursion. The reflections to follow take place in a Darwinian context: no matter how 'unique' or 'specific' one thinks recursion is, it simply won't do to appeal to equally unique or specific biological causes (i.e., mechanisms). Recursion, I take it, rests firmly on primate cognition and neural circuitry. As a matter of fact, the very nature of recursion — nothing more than re-applying a rule to its own output — suggests that it would be mistaken to look for a 'special solution' (a special mechanistic implementation): the rule itself must have existed ('descent'), and the constraint that prevented it from applying it to itself must have been lifted for recursion to emerge. It is the latter step, the lifting of the constraint, that the term 'modification' intends to capture: there must be descent, but there must have been some modification as well.

Obviously, the big question is, How much of a modification did there have to be? To some extent, the magnitude of the modification is a matter of perspective, and I will therefore not focus on this issue.[1] I will devote my attention to the nature of the modification itself. In line with my previous work (beginning with Boeckx, 2013a), I will implicate an independently

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[1] One reviewer asks if the current hypothesis could be seen as putting "flesh on the bones of proposals frequently made over the past few years by Chomsky, Berwick [and others] to the effect that a crucial step in the development of language in modern humans, the introduction of recursive hierarchical structure, may have involved a "slight rewiring" of the brain" (see, e.g., Berwick & Chomsky, 2016). It may be, but I am not too keen on this interpretation, as I do not know of any way of figuring out if the rewiring process was minor or not. It could have involved complex molecular changes that we presently don't understand. It also seems to me that the 'slight rewiring proposal' often goes hand in hand with a prominent interpretation of the Faculty of Language in the Narrow Sense (Hauser, Chomsky, & Tecumseh Fitch, 2002), which I am skeptical about, for (biological) reasons I discussed in Boeckx, 2013a.

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attested anatomical change in the history of our species to shed light on how recursion may have come about. The anatomical change in question I will refer to as "globularity".

There is strong evidence that modern humans, in contrast to the otherwise big-brained Neanderthals, "show a species-specific neomorphic hypertrophy of the parietal volumes, leading to a dorsal growth and ventral flexion (convolution) and consequent globularity of the whole structure" (Bruner, 2004, p. 279). As Neubauer, Gunz, & Hublin, 2010, and many studies since then,[2] have shown globularity requires a specific brain growth trajectory to emerge, which they dub the globularization phase, and which appears to be a departure from the primate-typical trajectory (attested in Neanderthals). According to Neubauer et al. the globularization phase coincides with the first year of life, at a point when the brain is the main driving force behind the shaping of the skull.[3] What interests me most here is that this distinct brain growth trajectory reconfigures the brain in several ways, as Hublin, Neubauer, & Gunz, 2015 and Bruner, 2010 have shown. It affects most clearly the parietal lobe (as well as the cerebellum, and the frontal pole).

I have put forward the hypothesis that globularization may have been the last modification step that made the human brain truly language-ready (Boeckx, 2013a, 2016; Boeckx and Benítez-Burraco, 2014 et seq.). Given the mosaic nature of outputs of a historical process like evolution, I do not mean to suggest that language-readiness is one thing (see also footnote 1). It has many parts, none of which is more important than any other. One of aspects of language-readiness is, unquestionably, recursion. The reason I will focus on this trait here is because of the attention it received in light of Hauser, Chomsky, and Fitch's (2002) influential paper on how to approach the problem of language evolution. But also, and mainly, because I don't think recursion and globularity — two independently well-established phenotypic traits of our species, one cognitive, the other, anatomical — have already been linked. Although, as I will point out, some of the key observations on which I will rely to make my case have a distinguished pedigree in neurolinguistics.

At first sight, it looks like linking a core aspect of language like recursion and globularity is not promising, given that the parts of the brain most affected by globularization mentioned above fall outside the classical language network. But it is increasingly obvious that the classical model, relying on Broca's region and Wernicke's region, is inadequate when it comes to capturing a complex cognitive domain like language. In recent years several state-of-the-art articles have called for a substantial broadening of the language network (Fedorenko & Thompson-Schill, 2014; Hagoort & Indefrey, 2014; Poeppel, Emmorey, Hickok, & Pylkkänen, 2012), and studies like Blank, Balewski, Mahowald, & Fedorenko, 2016 have shown that syntax recruits all the regions of this extended language network. The consensus now is that in addition to the classical, fronto-temporal areas, cortical and subcortical structures like the parietal lobe, the cerebellum, the basal ganglia, the hippocampus and the thalamus all contribute to the neurobiological infrastructure of language. For present purposes, the involvement of the parietal region is critical.

More directly related to globularity specifically, there is an old claim, due to Norman Geschwind (who did so much to make the classical model classical), that I'd like to revive and exploit in the context of recursion. Back in the 1960s, while reviewing cases of aphasia, Geschwind foresaw the importance of the parietal lobe for the language network. I think Geschwind was on the right track. The claim I'd like to make is that the reorganization and expansion of the parietal region at the heart of globularization significantly enhanced, indeed transformed, the connection between Broca's region and Wernicke's region. This latter connection (size of the relevant regions aside), attested in non-human primates, appears to be fairly ancient, and functionally conserved (Bornkessel-Schlesewsky, Schlesewsky, Small, & Rauschecker, 2015; Wilson et al. 2015). The basic, dual (ventral and dorsal) pathway connecting Broca's and Wernicke's region was already in place before our species became fully linguistic. The key modification, I will claim, is that the neuroanatomical reconfiguration of the parietal lobe brought about by globularization extended the Broca-Wernicke connection (to be precise, its dorsal dimension) into "Geschwind's territory", forming a fronto-parieto-temporal circuit that provides the basis for richer representational capacities, viz. recursive capacities.[4]

## 2. Hypothesis

Neuroanatomical evidence for an invasion of the parietal region in otherwise fronto-temporal networks is robust. Seminal studies like Catani & Jones, 2005, Dick & Tremblay, 2012, Hecht et al. 2013, and Mendoza & Merchant, 2014 have shown how deeply implicated in the language connectome (but also in music) the parietal region is (see also Catani & Bambini, 2014). Indeed, this evidence has been exploited by several neurolinguists to argue for a special importance of the 'dorsal' dimension of the language network. Thus, in a series of very influential papers (Friederici, 2011, 2012a, 2016 Friederici & Gierhan, 2013; Berwick, Friederici, Chomsky, & Bolhuis, 2013; Zaccarella and Friederici, 2016, and references therein), Friederici and colleagues have argued for a substantial role of the dorsal connection between Broca's and Wernicke's regions in the context of 'complex' syntax. In addition to arcuate-fasciculus-based direct fronto-temporal connection, already recognized by Wernicke

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[2] See Neubauer, 2014 for a detailed discussion of the techniques used to formulate their hypothesis.

[3] Recently, Ponce de León, Bienvenu, Akazawa, & Zollikofer, 2016 have argued that the key difference is established earlier (closer to the time of birth). I will not try to settle this issue here, as the hypothesis I make is broadly compatible with either option.

[4] Although, as a reviewer observes, there is quite a bit of similarity between humans and macaques, comprehensive surveys like Caminiti, Innocenti, & Battaglia-Mayer, 2015 reveal significant differences, along the lines of the disproportionate expansion of association cortices in the course of our evolution (Buckner & Krienen, 2013).