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Self-similarity and recursion as default modes in human cognition

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Humans generate recursive hierarchies in a variety of domains, including linguistic, social and visuo-spatial modalities. The ability to represent recursive structures has been hypothesized to increase the efficiency of hierarchical processing. Theoretical work together with recent empirical findings suggests that the ability to represent the self-similar structure of hierarchical recursive stimuli may be supported by internal neural representations that compress raw external information and increase efficiency.

In order to explicitly test whether the representation of recursive hierarchies depends on internalized rules we compared the processing of visual hierarchies represented either as recursive or non-recursive, using task-free resting-state fMRI data. We aimed to evaluate the relationship between task-evoked functional networks induced by cognitive representations with the corresponding resting-state architecture. We observed increased connectivity within Default Mode Network (DMN) related brain areas during the representation of recursion, while non-recursive representations yielded increased connectivity within the Fronto-Parietal Control-Network.

Our results suggest that human hierarchical information processing using recursion is supported by the DMN. In particular, the representation of recursion seems to constitute an internally-biased mode of information-processing that is mediated by both the core and dorsal-medial subsystems of the DMN. Compressed internal rule representations mediated by the DMN may help humans to represent and process hierarchical structures in complex environments by considerably reducing information processing load.

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1. Introduction

The ability to understand and generate complex hierarchical structures is a hallmark trait of human cognition. The investigation of the neural bases of hierarchical processing is thus essential to understand the foundations of human cognitive architecture.

Recursion is a cognitive faculty postulated to play a significant role in human hierarchical processing (Corballis, 2011; Fitch, 2010; Hauser, Chomsky, & Fitch, 2002). In particular, recursion is thought to be necessary to achieve infinite use of finite means, and hypothesized to be available exclusively to humans (Fitch, Hauser, & Chomsky, 2005; Hauser et al., 2002). A simple example of a recursive process is the generation of natural numbers using the formula $N_i = N_{i-1} + 1$, in which both sides of the "transformation" rule contain elements belonging to the category "N". This simple process allows the generation of the infinite set of natural numbers.

Recursion can be used to generate both hierarchical and non-hierarchical structures. However, infinite 'flat' sequences without hierarchy can also be generated using simple non-recursive processes. Parsing such 'flat' structures is achievable by non-human animals (Fitch & Friederici, 2012; Nelson, Conway, & Christiansen, 2001 for reviews), and it can be difficult to distinguish, from behavioral data, whether recursive or non-recursive processes were used. Because of these empirical difficulties and because humans are especially sophisticated in their ability to handle hierarchies (as in language, music and action sequencing), a core research focus concerning recursion investigates how it enhances the processing of hierarchical structures.

Hierarchies are tree-like organizations, where higher levels incorporate multiple lower levels in structural representations (Fitch & Martins, 2014). Tree-like organizations are common in nature and in the human environment (Fig. 1), and having the cognitive resources available to represent them can enable multiple useful behaviors. For instance, an individual able to represent the hierarchical structure of a social group will have obvious generalization advantages over an individual unable to represent the same group as hierarchically organized. In the same vein, an individual able to represent appropriate hierarchies as recursive (Fig. 2) will have advantages over individuals unable to project recursive structures to new hierarchical levels (Martins, Muršič, Oh, & Fitch, 2015; Martins, 2012). In particular, being able to represent the similarity between different levels of a hierarchy (hierarchical self-similarity) allows the use of this representation to extend the hierarchy to further levels beyond the given (Martins, 2012). In other words, representing hierarchical self-similarity affords the ability to build hierarchies of unlimited depth. Even if the depth is limited by performance and memory constraints, this kind of flexible representation would still be advantageous when parsing complex hierarchies with cross-level similarities such as in visual perception, music, language, theory of mind, complex action, mathematics and architecture (Eglash, 1997, 1998; Eisenberg, 2008; Friederici, Bahlmann, Friedrich, & Makuuchi, 2011; Friedrich & Friederici, 2009; Jackendoff & Lerdahl, 2006; Janszky, Mertens, Janszky, Ebner, & Woermann, 2006; Martins, 2012; Miller, 2009; Pinker & Jackendoff, 2005, Fig. 2).

Evidently, not all hierarchies exhibit this kind of self-similar structure, and humans use both recursive and non-recursive representations to generate and parse hierarchies. The interesting question is not whether humans *always* use recursive representations, but whether these are *available* to our cognitive apparatus, and how they are instantiated. Crucially, there is no inconsistency between the view that humans are sensitive to recursive structures, but can also process non-recursive structures, i.e., that some cognition is recursive and some cognition not. The core of the paradigm that we use in this experiment is the comparison between recursive and non-recursive representations of the same fractal stimuli (Martins, Fischmeister, et al., 2014). Thus, both our framework and our experiment are compatible with the view that humans are sensitive to both recursive and non-recursive rules.

It is important to note and forestall a potential formal criticism of our approach here: that mathematical proofs concerning recursion make crucial use of infinite sets, but our conceptual and empirical framework makes no mention of infinity. This is because one can never, in reality, observe infinite sets, or expect humans to produce infinite numbers of sentences. Our central goal in this research program is to devise empirical tests for recursive abilities in different cognitive domains, and to understand the neural bases of such abilities. To accomplish this, we perforce rely on behavioral output which indicates one of the core properties of recursion: self-embedding. A mathematician might complain that, even by showing multiple levels of self-embedding, we have not "proven" recursion, because we cannot show that such embedding could go on forever. But this is equally true of ANY psychological evaluation: if we test a subject on addition and they correctly add together 100 pairs of random integers, we conclude that they can add integers – even if they haven't demonstrated an ability to add all possible integers. We see our focus on an empirically-evaluated ability to correctly process self-embedded structures as analogous, and interpret our results as solid evidence for recursive abilities; even though we do not test whether (or claim that) our participants can process infinite-depth structures. Any definition of recursion which relies on infinity as its *sine qua non* is, by definition, empirically untestable. A similar approach has been used by other authors (e.g., Moro, 2015 for a review).

Recursion, understood as a cognitive ability useful for the generation of complex hierarchies, was first thought to be language domain-specific (Hauser et al., 2002), and most of the available theoretical and empirical work has focused on this domain. However, recent research has shown that both human adults and children are able to represent hierarchies using recursion in the visuo-spatial domain (Martins, Laaha, Freiberger, Choi, & Fitch, 2014). This capacity is independent of verbal resources (Martins et al., 2015) and does not recruit classical perisylvian language areas in the brain (Martins, Fischmeister, et al., 2014).

The independence of visual recursion from verbal resources and language brain areas suggests that the instantiation of recursion in vision partially depends on different cognitive and neural resources than in language. For