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Cognitive representation of "musical fractals": Processing hierarchy and recursion in the auditory domain

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ABSTRACT

The human ability to process hierarchical structures has been a longstanding research topic. However, the nature of the cognitive machinery underlying this faculty remains controversial. Recursion, the ability to embed structures within structures of the same kind, has been proposed as a key component of our ability to parse and generate complex hierarchies. Here, we investigated the cognitive representation of both recursive and iterative processes in the auditory domain. The experiment used a two-alternative forced-choice paradigm: participants were exposed to three-step processes in which pure-tone sequences were built either through recursive or iterative processes, and had to choose the correct completion. Foils were constructed according to generative processes that did not match the previous steps. Both musicians and non-musicians were able to represent recursion in the auditory domain, although musicians performed better. We also observed that general 'musical' aptitudes played a role in both recursion and iteration, although the influence of musical training was somehow independent from melodic memory. Moreover, unlike iteration, recursion in audition was well correlated with its non-auditory (recursive) analogues in the visual and action sequencing domains. These results suggest that the cognitive machinery involved in establishing recursive representations is domain-general, even though this machinery requires access to information resulting from domain-specific processes.

1. Introduction

The capacity to represent and generate hierarchical structures is a fundamental human trait that is used in virtually every domain of activity. Even though this trait is to some extent present in other species (Bergman, Beehner, Cheney, & Seyfarth, 2003; Massen, Pašukonis, Schmidt, & Bugnyar, 2014; Seyfarth & Cheney, 2008; Seyfarth, Silk, & Cheney, 2014), it seems to be especially developed in humans (Conway & Christiansen, 2001; Fitch & Friederici, 2012; Hauser, Chomsky, & Fitch, 2002; ten Cate & Okanoya, 2012; Vasconcelos, 2008). Not only are human-generated hierarchies more complex, but they are also more general, since the average person can generate visual, social, linguistic and action hierarchies (Altmann, Bülthoff, & Kourtzi, 2003; Badre, 2008; Badre & D'Esposito, 2009; Badre, Hoffman, Cooney, & D'Esposito, 2009; Bahlmann, Schubotz, & Friederici, 2008; Chomsky, 1995; Eglash, 1998; Fitch & Martins, 2014; Friederici, 2011; Hunyady, 2010; Jackendoff, 2003; Jackendoff, 2009; Kravitz, Saleem, Baker, & Mishkin, 2011; Picard et al., 2010; Zink et al., 2008). This complexity and generality could be explained either by a general increase in processing power, due to a larger brain, or by the existence of additional specialized processes or abilities in human cognitive architecture.

One such ability, which could potentially explain the human cognitive exceptionality, is recursion (Hauser et al., 2002). Recursion can be understood as the ability to embed elements within elements of the same kind (Fitch, 2010; Hulst, 2010; Martins, 2012). Recursion is a particular principle to represent and generate hierarchies which allows the generation of multiple levels with a single rule (Fig. 1B).

This increased generative power of recursion in comparison with other kinds of hierarchical principles is thought of as being instantiated by cognitive representations of a higher level of abstraction (Martins, 2012). For instance, instead of representing each hierarchical relation with its own rule, of the kind $A \rightarrow B$ and $B \rightarrow C$ (Fig. 1A), humans are able to understand that these

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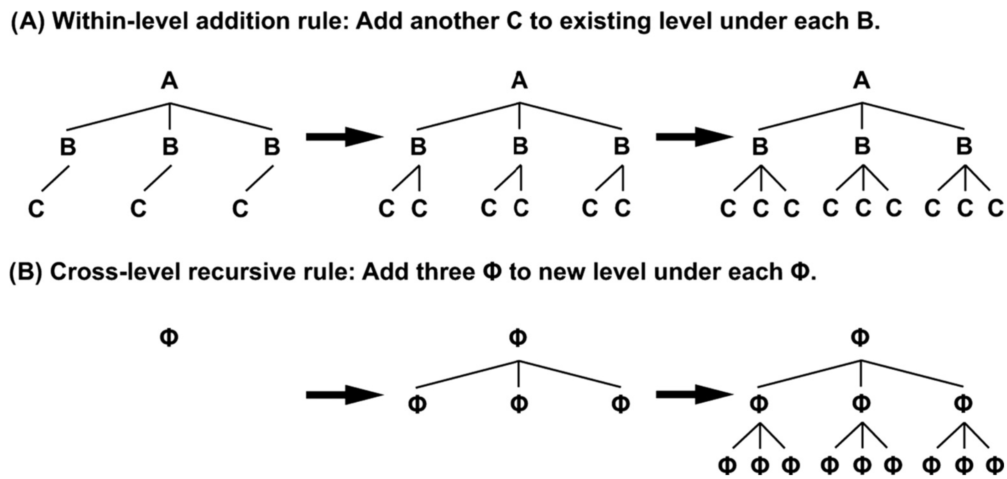

Fig. 1. Recursive and non-recursive procedures to generate hierarchies. (A) Simple iterative procedures add elements to a hierarchy, within fixed levels. In order to generate a level under 'C', another rule would be required – add another 'D' under each 'C'. (B) Recursive rules are more abstract. They can be used to characterize hierarchical relations across many different levels of the hierarchy. With the same rule (B), an infinite number of hierarchical levels could be added to the structure.

relations have commonalities, which allows the induction of a more general rule $\Phi \rightarrow \Phi$ (Fig. 1B). To our knowledge, this level of hierarchical abstraction seems to be specifically available to human cognition (Berwick, Friederici, Chomsky, & Bolhuis, 2013; Fitch, Hauser, & Chomsky, 2005; Hauser et al., 2002; ten Cate & Okanoya, 2012).

1.1. Cognitive assessment of recursion

Formally, structures that can be understood as recursive have been suggested to exist in visual art (Eglash, 1997), visuo-spatial processing (Martins, 2012; Martins & Fitch, 2012), music (Jackendoff & Lerdahl, 2006; Lerdahl & Jackendoff, 1996), architecture (Eglash, 1998), humour (Eisenberg, 2008), theory of mind (Miller, 2009; Tomasello, 2008), problem solving (Schiemenz, 2002), action sequencing (Pulvermüller & Fadiga, 2010), syntax (Chomsky, 1995; Karlsson, 2010; Mithun, 2010; Roeper, 2009), phonology (Hulst, 2010; Hunyady, 2010; Schreuder, Gilbers, & Quené, 2009; Wagner, 2010), pragmatics (Levinson, 2013), conceptual structure (Hofstadter, 2000; Picard et al., 2010), mathematical proofs (Odifreddi, 1999), natural numbers (Hauser et al., 2002), and arithmetic operations (Friederici, Bahlmann, Friedrich, & Makuuchi, 2011). In all these domains it is possible to build recursive algorithms that generate hierarchical structures. However, it is not clear that in all these domains humans actually represent the recursive character of these structures, and use these representations productively. Such demonstrations require empirical rather than theoretical tools.

To our knowledge, the ability to induce recursive rules was empirically demonstrated first in the linguistic domain (Alegre & Gordon, 1996; Roeper, 2011). In this domain, recursion seems to be universally used (Reboul, 2012), and although some researchers argue that it is rare in common speech (Laury & Ono, 2010), most language users in the world are likely to have generated multiple recursive sentences in their lifetimes (for instance, compound noun phrases such as "[[[student] film]] committee]"). Furthermore, the ability to extract the correct meaning from recursive sentences seems to be available early during ontogeny (Alegre & Gordon, 1996; Roeper, 2009). This interesting relationship between language and recursion, yet undemonstrated in other domains, has led some authors to propose that recursion is a domain-specific "linguistic computational system [...], independent of the other systems with which it interacts and interfaces" (Fitch et al., 2005; Hauser et al., 2002). This hypothesis implies that the use of recursion in other domains is dependent on verbal resources. Coincidentally, the ability to perform second-order theory of mind tasks (e.g., [I think that [she thinks that [John thinks something]]]) correlates with language abilities (Miller, 2009, for a review), and verbal interference tasks block the ability to use natural numbers (Gordon, 2004). These results were taken as strong evidence that recursion is a linguistic domain-specific ability.

Recently, in a series of experiments, human adults and children have also been shown to represent recursion in the visuo-spatial domain (Martins, Fischmeister, et al., 2014; Martins, Laaha, Freiberger, Choi, & Fitch, 2014; Martins, Mursic, Oh, & Fitch, 2015). In this domain, subjects were able to induce recursive rules generating visual fractals, and to use these rules productively. Crucially, this ability was not specifically related with grammar comprehension (Martins, Laaha, et al., 2014), and it neither required verbal resources (Martins et al., 2015), nor generated activation in classical language brain areas (Martins, Fischmeister, et al., 2014). However, performance correlated with an action sequencing task, the Tower of Hanoi, which is best solved using recursive strategies (Martins, Fischmeister, et al., 2014).

These findings suggest that recursion does not necessarily require linguistic resources (arguing against the primacy of language). However, it is still possible that the same cognitive machinery is used to implement recursion in both domains (language and vision), if a domain-general (abstract) code were used instead of a linguistic or verbal one (Martins et al., 2015).

In this paper, we aim to expand our understanding of recursion in human cognition by focusing on another non-linguistic domain – using acoustic stimuli – and measure how recursive capacities in this domain correlate with recursion in other domains. Towards this goal, we will assess how humans represent "musical fractals".

1.2. Hierarchical processing of music

Like language, music is a domain known to require the processing of hierarchical relations (Jackendoff, 2009; Jackendoff & Lerdahl, 2006; Koelsch, Rohrmeier, Torrecuso, & Jentschke, 2013; Rohrmeier, 2011). These relations involve the embedding of discrete acoustic events into higher-order structures, according to their rhythmical and pitch relationships. For instance, in tonal structures, there are precise relations between tones and the context in which these tones are embedded. Thus, in Western music, the same tone (or chord) can be perceived as decreasing or increasing the tension of a musical sequence according to the context,