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How children perceive fractals: Hierarchical self-similarity and cognitive development

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ABSTRACT

The ability to understand and generate hierarchical structures is a crucial component of human cognition, available in language, music, mathematics and problem solving. Recursion is a particularly useful mechanism for generating complex hierarchies by means of self-embedding rules. In the visual domain, fractals are recursive structures in which simple transformation rules generate hierarchies of infinite depth. Research on how children acquire these rules can provide valuable insight into the cognitive requirements and learning constraints of recursion.

Here, we used fractals to investigate the acquisition of recursion in the visual domain, and probed for correlations with grammar comprehension and general intelligence. We compared second ($n = 26$) and fourth graders ($n = 26$) in their ability to represent two types of rules for generating hierarchical structures: Recursive rules, on the one hand, which generate new hierarchical levels; and iterative rules, on the other hand, which merely insert items within hierarchies without generating new levels. We found that the majority of fourth graders, but not second graders, were able to represent both recursive and iterative rules. This difference was partially accounted by second graders' impairment in detecting hierarchical mistakes, and correlated with between-grade differences in grammar comprehension tasks. Empirically, recursion and iteration also differed in at least one crucial aspect: While the ability to learn recursive rules seemed to depend on the previous acquisition of simple iterative representations, the opposite was not true, i.e., children were able to acquire iterative rules before they acquired recursive representations. These results suggest that the acquisition of recursion in vision follows learning constraints similar to the acquisition of recursion in language, and that both domains share cognitive resources involved in hierarchical processing.

1. Introduction

The ability to represent and generate complex hierarchical structures is one of the hallmarks of human cognition. In many domains, including language, music, problem-solving, action-sequencing, and spatial navigation, humans organize basic elements into higher-order groupings and structures (Badre, 2008; Chomsky, 1957; Hauser, Chomsky, & Fitch, 2002; Nardini, Jones, Bedford, & Braddick, 2008; Unterrainer & Owen, 2006; Wohlschlager, Gattis, & Bekkering, 2003). This ability to encode the relationship between items (words, people,

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etc.) and the broader structures where these items are embedded (sentences, corporations, etc.), affords flexibility to human behavior. For example, in action sequencing, humans are able to change, add, or adapt certain basic movements to particular contexts, while keeping the overall structure (and goals) of canonical motor procedures intact (Wohlschlager et al., 2003).

The ability to process hierarchical structures develops in an interesting way. Young children seem to have a strong bias to focus on the local information contained within hierarchies. For instance, in the visual-spatial domain, while attending to a big square composed of small circles, children have a tendency to identify the small circles faster and easier than they can identify the big square (Harrison & Stiles, 2009; Poirel, Mellet, Houdé, & Pineau, 2008). This local-oriented strategy to process hierarchical stimuli is similar to non-human primates (Fagot & Tomonaga, 1999; Spinozzi, De Lillo, & Truppa, 2003), and it usually precludes adequate hierarchical processing. Conversely, in human adults a global bias develops, in which global aspects of hierarchical structures are processed first, and where the contents of global information interfere with the processing of local information (Bouvet, Rousset, Valdois, & Donnadieu, 2011; Hopkins & Washburn, 2002). This ability to represent items-in-context is one of the pre-requisites of hierarchical processing. In other domains such as in language, children display equivalent impairments: they seem to grasp the meaning of individual words, and of simple adjacent relationships between them, but display difficulties in extracting the correct meaning of sentences containing more complex constructions (Dąbrowska, Rowland, & Theakston, 2009; Friederici, 2009; Roeper, 2011). This progressive development in the ability to integrate local and global information within hierarchies seems to be associated with brain maturational factors (Friederici, 2009; Moses et al., 2002), but also with the amount of exposure to the particular kinds of structures that children are asked to process (Roeper, 2011).

In this study, we are interested in investigating a particular aspect of hierarchical processing, which is the ability to encode hierarchical self-similarity. Hierarchies can be generated and represented using processes that establish relationships of dominance and subordination between different items (Martins, 2012). Some of these processes are depicted in Fig. 1. For instance, 'iterative rules' (Fig. 1A) can be used to represent the successive addition of items to a structure, such as the addition of beads to a string to form a necklace. 'Embedding rules' can also be used to generate hierarchies by embedding one or more items into a structure so that they depend on another item (Fig. 1B). For example, in an army hierarchy, two brigades can be incorporated into a division. Finally, we can also use 'recursive embedding rules' to generate and represent hierarchies. Recursive embedding, or simply 'recursion', is the process by which we embed one or more items as dependents of another item of the same category (Fig. 1C). For example, in a compound noun we can embed a noun inside another noun, as in [[student] committee]. As we can see from Fig. 1, recursion is interesting and unique because it allows the generation of multiple hierarchical levels with a single rule.

One important notion to retain here is that recursion can be defined either as a "procedure that calls itself" or as the property of "constituents that contain constituents of the same kind" (Fitch, 2010; Pinker & Jackendoff, 2005). Frequently, we find an isomorphism between procedure and structure, i.e., recursive processes often generate recursive structures. However, this isomorphism does not always occur (Lobina, 2011; Luuk & Luuk, 2010; Martins, 2012). In this manuscript we explicitly focus on the level of representation, i.e., we focus on detecting *what* kind of information individuals can represent (i.e. hierarchical self-similarity), rather than on *how* this information is implemented algorithmically.

The ability to perceive similarities across hierarchical levels (i.e. hierarchical self-similarity) can be advantageous in parsing complex structures (Koike & Yoshihara, 1993). On the one hand, representing several levels with a single rule obviously reduces memory demands. On the other hand, this property allows the generation of new (previously absent) hierarchical levels without the need to learn or develop new rules or representations. This ability to represent hierarchical self-similarity, and to use this information to make inferences allows all the cognitive advantages postulated as being specifically afforded by 'recursion' (Fitch, 2010; Hofstadter, 1980; Martins, 2012; Penrose, 1989), namely the possibility to achieve infinity from finite means (Hauser et al., 2002).

One famous class of recursive structures is the fractals. Fractals are structures that display self-similarity (Mandelbrot, 1977), so that they appear geometrically similar when viewed at different scales. Fractals are produced by simple rules that, when applied iteratively to their own output, can generate complex hierarchical structures. Since the same kind of representation can be used at different levels of depth, simple rules suffice to represent the entirety of the structure. An example of a process generating a visuo-spatial fractal is depicted in Fig. 2. Here, a simple recursive rule adds a triad of smaller hexagons around each bigger hexagon. Since the relations between successive hierarchical levels are kept constant, individuals who are able to generate mental representations of recursion can make inferences about new (previously absent) hierarchical levels (Martins, 2012). This is the principle that we use in our investigation (For more details, see Appendix A). Our goal was to investigate how the ability to represent hierarchical self-similarity develops in the visual domain, and how this ability can be predicted by individual differences in intelligence, grammar comprehension and general visual processing.

The ability to represent hierarchical self-similarity has been empirically tested in the syntactic domain and in the visual domain (Martins & Fitch, 2012; Roeper, 2007). However, the developmental aspects of this ability have only been investigated in language (Roeper, 2011). In the next sections we briefly review what is currently known, and why it is important to extend this analysis to the visual-spatial domain.