DIFFERENCE OF TWO RECURSIONS, "HIERARCHICAL EMBEDDING" AND "SELF-REFERENCE": FROM VIEW OF ADAPTIVE FUNCTIONS AND IMPLEMENTATIONS

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"Recursion" is understood in two ways: 1) "hierarchical embedding" as a structure and 2) "self-reference / self-invocation of a function" as an operation. The former refers to structure itself, and the latter refers to an operation[1] to create the structure. In research of language and comparative cognition between humans and non-human animals, these two kinds of "recursion" were sometimes confused and misunderstood (Martins, 2012). In the current talk, we demonstrate that the conceptual essence of recursive operation is not the existence and generation of a certain hierarchical embedded structure, but a function which calls itself to create a new embedded structure indefinitely. Additionally, we suggest that the ecological environment of humans is likely to have made the latter adaptive, and the human brain has neural infrastructure that realizes recursive operation. Finally, from research on bird songs, human uniqueness of the recursive operation is discussed.

Goal-directed behavior in human beings includes not only non-recursive operation which is generally observed in non-human animals but also recursive operation in which parts of sequence are maintained so that it can be combined with other parts of sequence and arranged to have a particular form. However, the recursive operation requires a higher cognitive load to hold temporal processes. An evolutionary simulation study showed that the adaptive significance of self-

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[1] In our previous paper (Toya and Hashimoto, 2017), this operation is called "recursive combination operation."

reference in object manipulation is to produce complex and diverse products such as stone tools (Toya and Hashimoto, 2015) in a highly competitive environment for resources (Toya and Hashimoto, 2017). Such environment may be realized from 2.5 million years ago with forest lands decreasing in the human evolution (Bobe and Behrensmeyer, 2004; deMenocal, 2011). The results of those simulations showed that recursive operation is required to achieve diverse goals although non-recursive operation has a lower cost than recursive operation. This consideration opens up a new perspective to relate recursive operation to a neural mechanism.

We hypothesize that recursive operation is implemented in the brain by focusing on the functionary segregated cortico-basal ganglia-thalamocortical (CBGT) circuits. The CBGT circuits are suggested to be necessary for working memory (Lustig, 2005; Hochstadt, 2006) and cognitive control (Monchi et al., 2001; Lieberman, 2002) in which maintenance and manipulation of temporal events play a significant role. Both two functions are crucial for realizing recursive operation.

Does a neural mechanism for recursive operation exist in other animals? In bird songs, basic elements are combined into chunks, which combined into phrases, which combined into whole sequence. Songbirds learn and use processing rules of these songs in separate brain modules for each level of the hierarchy (Okanoya, 2004; Okumura et al., 2011). This mechanism seems to be different from the recursive operation because songbirds do not generate new structure which do not belong to learned set. Therefore, we suggest that recursive operation is not required for reproducing hierarchical embedding of learned songs.

In conclusion, humans possess the ability of "recursive operation" with self-reference, which leads to creativity that is not found in the hierarchical embedding for learning-reproduction system such as the song of songbirds.

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