Further Thoughts on the Paper by Tani
"Self-Organization and Compositionality in Cognitive Brains"

Jun Tani, Karl Friston and Simon Haykin

(Proceedings of the IEEE, Special Issue on Cognitive Dynamic Systems, Vol. 102, no. 4, pp. 606—607, 2014.)

Key words and index terms

Symbol grounding problem, self-organization, compositionality, neuro-robotics, chaos, embodied cognition, dynamical systems, neural network models, sensory-motor systems

The symbol grounding problem as understood today can be traced back at least to Cartesian dualism and medieval times. René Descartes postulated that the mind is an immaterial thinking thing essentially distinct from the non-thinking material body, only then to face the 'problem of interactionism,' i.e. explaining how an immaterial mind can cause anything in a material body, and vice versa. Today's symbol grounding problem addresses the same concern, asking how symbols understood as arbitrary shapes or tokens defined in non-metric space can interact densely with sensory-motor reality defined in an effectively physical and material metric space.

In the paper entitled "Self-organization and compositionality in cognitive brains: a neuro-robotic study" [1], Jun Tani attempts to constructively resolve this long-standing problem of mind and body. The paper details experimental trials, inspired by Merleau-Ponty's philosophy of embodiment, in which Tani has engineered self-organizing non-linear dynamic systems into robotic platforms in order to test the conjecture that neuro-dynamic structures self-organize via accumulated learning of the continuous flow of sensory-motor experience. This learning grounds higher-level cognition in perceptual reality without suffering the disjunction between lower- and higher-level operations found in hybrid models employing symbolic compositional operations. Instead, iterative interactions between top-down subjective intentional processes (acting on the objective world) and the bottom-up recognition of perceptual reality result in the modification of top-down intention by circular causality. As such, Tani's models demonstrate what Merleau-Ponty metaphorically described as the reciprocal insertion and intertwining of one (the subject) and the other (the object) through which those two become inseparable entities [2].

This sketch might not be easily appreciated by proponents of cognitivism such as that laid out by Chomsky in response to Skinner's behaviorism, i.e. that symbolic

language cannot be acquired merely through conditioning, as the cognitivist may assume the following two aspects of human cognition. The first assumption may be that an essential aspect of human cognition can be adequately described in terms of logical symbol systems, the great strength of which being that they can support an infinite range of recursive expressions. And, the second assumption may be that a less- or non-essential sensory-motor or semantic system is not necessary for the composition or recursion taking place in terms of such symbol systems, either at all or at least not in any noteworthy depth [3]. The crucial question for Tani, here, is whether it is necessary for the daily behaviors and thoughts of human beings to be supported by such an infinite range of recursive compositions, or not. In normal situations, he argues, human beings speak only with a limited depth of embedded sentences, and make action plans composed of only a limited length of primitive sequences at each level. In neither case is an infinite depth of recursive compositions required. And, the series of experimental studies that he describes in his contribution to this issue confirms this characterization [1]. Recurrent neural networks (RNN) can learn to mimic stochastic sequences through self-organizing deterministic chaos with the complexity of finite state machines, but not with that of infinite ones. Although mathematical study [4] has established the possibility that analog computational models, including RNNs, can exhibit a computational capability beyond the Turing limit, the construction of such Turing machines through learning is practically impossible because the corresponding connectivity weights can be found only in non-measurable points in the weight space. And, to make matters worse, even if an equivalence of such a Turing machine could be reconstructed in an RNN by chance, such a parameter-sensitive system may not function reliably, situated in the noisy sensory-motor reality that its practical embodiment may require.

This situation should be the same for ordinary human cognitive processes which rely on working memory of relatively limited size and accuracy. Psychological studies have shown that humans cannot learn to predict string sequences generated by finite state machines if the number of their states becomes more than 3 or 4 [5]. However, human beings have extended this capacity through the use of external devices, such as pencil and paper, to record linguistic symbols representing thoughts and to experiment with their composition. When human beings need to construct complicated sentences or complicated action plans for the first time, they typically compose them on paper utilizing symbols. If a human being were permitted the use of an infinite space for such compositions, then he/she may be able to compose infinite expressions through the available infinite depth of recursion. And, the same should hold for an RNN likewise

empowered with such unlimited resources [6].

Tani's paper is not intended to address the Chomskyan who holds that this capacity for infinite expression without the aid of external devices is the hallmark of human cognition. Rather, his contribution focuses on everyday analogical processes generating behaviors and thoughts characterized by an everyday degree of compositionality. This scope may be thought to include the daily utterances of children who, before elementary school, can compose sentences in their mother language without explicitly recognizing their syntactic structures, and to include the tacit learning of skilled behaviors such as grasping an object in order to pass it to others without thinking about it. On the basis of experimental demonstrations of the development of these sorts of capabilities, Tani's paper then demonstrates that the self-organization of particular dynamic structures within neuro-dynamic models can develop a finite level of compositionality and that, throughout this process, the contents of these compositions remain naturally grounded in the ongoing flow of perceptual reality. Thus, Tani's aim is twofold. First, he presents compelling experimental evidence that the dynamically embodied development of higher-level compositionality at finite levels should be considered the hallmark of human cognition. And second, his experimental results suggest that "extended minds" [7], with potentially infinite expressive power through the seamless integration of native brain resources with such external resources as pen and paper, books and even the Internet, might be naturally grounded because of - and through - these same developmental dynamics. This is worthy of contemplation as modern life and cognition depend on such external resources, also representing one important direction for Tani's future studies in this area.

Reference

[1] Tani, "Self-organization and compositionality in cognitive brains: a neuro-robotics study," vol. ? no. ?, pp. ?-?, 2014.

[2] M. Merleau-Ponty, *The Visible and the Invisible: Followed by Working Notes (Studies in phenomenology and existential philosophy)*. Northwestern University Press, 1968.

[3] M. D. Hauser, N. Chomsky, and W. T. Fitch, "The faculty of language: What is it, who has it, and how did it evolve?," Science, vol. 298, no.5598, pp. 1569-1579, 2002.

[4] H. T. Siegelmann, "Computation beyond the Turing limit," *Science*, vol. 268, no. 5210, pp. 545-548, 1995.

[5] A. Destrebecqz and A. Cleeremans, "Can sequence learning be implicit? New

evidence with the process dissociation procedure," *Psychonomic Bulletin & Review*, vol. 8, no. 2, pp. 343-350, 2001.
[6] S. Das, C. L. Giles, and G. Z. Sun, "Learning context-free grammars: Capabilities and limitations of a recurrent neural network with an external stack memory," In Proceedings of The Fourteenth Annual Conference of Cognitive Science Society, Indiana University, 1992.
[7] A. Clark and D. Chalmers, "The extended mind," *Analysis*, pp. 7-19, 1998.