Embodiment, Information, and Causal Structure

Max Lungarella[1] and Olaf Sporns[2]

[1]Department of Mechano-Informatics, University of Tokyo, 113-8656 Tokyo, Japan
[2]Department of Psychological and Brain Sciences, Indiana University, Bloomington IN 47405, USA
maxl@isi.imi.i.u-tokyo.ac.jp

Abstract

Evidence from neuroscience and developmental psychology suggests that correlations, redundancies, and invariances in sensory and motor patterns are critical for enabling perceptual categorization, adaptation, learning, and developmental processes. A major challenge is to understand how the brain extracts such statistical regularities in real time from the huge amount of information relayed to it. We argue that by tying information processing to embodiment the problem can be simplified. Embodied agents such as humans and robots are not exposed to unstructured sensory information. Courtesy of their behaviors and their morphologies, their sensory inputs are structured and the multimodal data relayed to their "cognitive" architectures have statistical regularities. Behavior and morphology inform and shape cognition which is the outcome of the dynamic interplay of physical and information theoretic processes, and not the end result of a control process that can be understood at any single level of analysis. But how does embodiment actively support and promote intelligent information processing? How does embodiment support to the structuring of sensory inputs? How can the dynamics of the physical interaction between an embodied system and its surrounding environment be quantified and exploited?

To provide answer to such questions and *en route* to a theory of embodied information processing, we point out some design principles (or guidelines) aimed at capturing heuristics and design ideas in a concise way. Our research efforts can be roughly segmented into three inter-linked categories. The first category is concerned with *methods* quantifying information structure contained in sensory and motor channels of embodied systems (Lungarella et al., 2005; Lungarella et al., 2006; Pitti et al., 2005). We exemplified how such measures can be used by applying them to a robot capable of saliency-based attentional behavior (Lungarella et al., 2005), a ring-like structure (Pitti et al., 2005), humanoid and quadrupedal robots (Sporns et al., 2006), as well as to evolve sensorimotor coordinated behavior in a simple creature (Sporns and Lungarella, 2006). We found that effectively coordinated motor activity can lead to patterns of decreased entropy, and increased mutual information, integration and complexity in sensory data.

We also introduced and discussed methods for identifying, quantifying, and classifying (potentially invariant) local features and global patterns that emerge from sensorimotor dynamics and embodied interaction: complexity and integration in (Lungarella et al., 2005; Sporns and Lungarella, 2006) and a set of novel tools based on spectral and wavelet analysis in (Pitti et al., 2005).

In order to extract undirected and directed informational exchanges between coupled systems, such as brain, body, and environment, we also studied a set of measures aimed at detecting asymmetric couplings and directional information flow between coupled systems (Lungarella et al., 2006). We applied one of these measures (transfer entropy; Sporns et al., 2006), and found that patterns of non-causal as well as causal relations exist which can be mapped between a variety of sensor and motor variables sampled by morphologically different robotic platforms (a humanoid robot, a wheeled mobile robot, and a quadruped). Our analyses revealed specific patterns of causality which are (a) quantifiable and variable in magnitude; (b) temporally specific with peaks located at offsets +1 and -1 time steps, and (c) spatially specific, that is, image portions in the center of the visual field display significant transfer entropy, while peripheral areas in many cases exhibit no causal relations.

The second research category deals with the principle of information self-structuring, that is, the ability of embodied agents to *actively* structure their sensory input and to generate statistical regularities in their sensory and motor channels. Our view is expressed by a fundamental principle of adaptive behavior

(Lungarella et al., 2005): *"Embodied agents do not passively absorb sensory information from their surrounding environment, but through their actions on the environment; they proactively structure, select, and exploit information."* This principle points to the critical role played by the mutual interaction between body, control structure, and environment to induce statistical regularities and informational structure at various functional levels of the control architectures and at multiple spatial and temporal scales. Its implications for learning are two-fold. First off, the structure of the sensory inputs and the one of the neural activity are interdependent and cannot be separated – learning heavily relies on both of them. Indeed, structured sensory input facilitates complex neural dynamics and high matching between perceived environmental structure and neural connectivity. The second implication is that sensorimotor activity and embodiment can actually generate statistical (intra and inter-modal) structure in the sensory inputs and should therefore be exploited. In (Sporns and Lungarella, 2006), we showed how maximizing information structure is highly effective in generating coordinated behavior in a simulated creature subject to behavioral and information theoretic cost functions. We suggest that embodied interaction lies at the root of a powerful learning mechanism as it enables the creation of time-locked correlations and the discovery of higher-order regularities that transcend the individual sensory modalities.

A third research category is related to the generation of structured patterns of sensory stimulation through the interaction of the intrinsic dynamics given by a particular morphology with the surrounding environment. The specific morphology of the body and its natural dynamics shape the repertoire of preferred movements (without requiring too much control). It follows that part of the "processing" can be taken over by the dynamics of the agent-environment interaction, and that only sparse (but well-timed) neural control needs to be exerted if the self-regulating and stabilizing properties of the natural dynamics are exploited. A paradigmatic example is provided by passive dynamic walkers – robots that can walk down slopes without control or actuation. To get such a robot to walk on a level surface, one need only endow it with actuators – the robot's natural dynamics stabilizes the limit cycle trajectory that the robot follows and learning is sped up. The idea that brain, morphology, materials, and environment share responsibility in generating information structure has been called the "principle of ecological balance" (Pfeifer et al., 2006) because there is a balance or task distribution among the different aspects of an embodied agent.

The conceptual view of *perception as an active process* has gained much support in recent years. Our work provides additional evidence for this view and proposes a new link between embodiment and information. Perception cannot be treated as a purely computational problem that unfolds entirely *within* a given information processing architecture. Instead, perception is naturally embedded within a physically embodied system, interacting with the real world. It is the *interplay* between physical and information processes that gives rise to perception. Our research aims at paving the way towards a formal and quantitative analysis of the specific contributions of embodiment to perceptual processing through the active generation of structure in sensory stimulation. The idea of inducing information structure through physical interaction with the real world has important consequences for understanding and building intelligent systems, and highlights the fundamental importance of morphology, materials, and dynamics.

References

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