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INVITED ARTICLE

Embodied cognition, embodied regulation, and the Data Rate Theorem

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Abstract
The Data Rate Theorem that establishes a formal linkage between linear control theory and information theory carries deep implications for the design of biologically inspired cognitive architectures (BICAs), and for the more general study of embodied cognition. For example, modest extensions of the theorem provide a spectrum of necessary conditions dynamic statistical models that will be useful in empirical studies. A large deviations argument, however, suggests that the stabilization of such systems is itself an interpenetrating dynamic process necessarily convoluted with embodied cognition. As our experience with mental disorders and chronic disease implies, evolutionary process has had only modest success in the regulation and control of cognitive biological phenomena. For humans, the central role of culture has long been known. Although a ground-state collapse analogous to generalized anxiety appears particularly characteristic of such systems, lack of cultural modulation for real-time automatons or distributed cognition man-machine 'cockpits' makes them particularly subject to a canonical pathology under which 'all possible targets are enemies'. Concerted attention to cognitive theories of 'mental dysfunction' across human, man-machine cockpit, and fully-machine modalities is needed, particularly in view of a successful BICA effort that would make highly complex automata that interact with humans ubiquitous.

Introduction

According to Samsonovich (2012),

> The BICA Challenge is the challenge to create a general-purpose, real-life computational equivalent of the

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human mind using an approach based on biologically inspired cognitive architectures.... To solve it, we need to understand at a computational level how natural intelligent systems develop their cognitive, metacognitive and learning functions. The solution is expected to lead us to a breakthrough to intelligent agents integrated into the human society as its members.

Natural cognitive systems operate at all scales and levels of organization of biological process (e.g., Wallace, 2012, 2014). The failure of low level biological cognition in humans is often expressed through early onset of the intractable chronic diseases of senescence (e.g., Wallace & Wallace, 2010, 2013). Failure of high order cognition in humans has been the subject of intensive scientific study for over two hundred years, with little if any consensus. As Johnson-Laird, Mancini, and Gangemi (2006) put it,

Current knowledge about psychological illnesses is comparable to the medical understanding of epidemics in the early 19th century. Physicians realized that cholera, for example, was a specific disease, which killed about a third of the people whom it infected. What they disagreed about was the cause, the pathology, and the communication of the disease. Similarly, most medical professionals these days realize that psychological illnesses occur...but they disagree about their cause and pathology.

This conclusion carries important implications for any BICA program, and indeed, for any systematic attempts to automate complex mission-critical real-time cognitive processes, be they network management, industrial production, vehicle control, or automated combat systems.

And as the press chatter surrounding the release of the latest official US nosology of mental disorders — the so-called 'DSM-V' — indicates, this may be something an understatement. Indeed, the entire enterprise of the *Diagnostic and Statistical Manual of Mental Disorders* has been characterized as 'prescientific' (e.g., Gilbert, 2001). Atmanspacher (2006) further argues that formal theory of high-level cognition is itself at a point like that of physics 400 years ago, with the basic entities and the relations between them yet to be determined. Further complications arise via the overwhelming influence of culture on both mental process and its dysfunction (e.g., Heine, 2001; Kleinman & Cohen, 1997), something to which we will eventually return. See Chapter 5 of Wallace and Wallace (2013) for a more detailed summary of these matters.

The overall inference is that stabilization and regulation of high order cognition may be as difficult as the BICA Challenge itself.

Varela, Thompson, and Rosch (1991), in their study *The Embodied Mind: Cognitive Science and Human Experience*, asserted that the world is portrayed and determined by mutual interaction between the physiology of an organism, its sensimotor circuitry, and the environment. The essential point, in their view, being the inherent structural coupling of brain-body-world. Lively debate has followed and continues (e.g., Clark, 1998; Wilson, 2002; Wilson, 2013). Brooks (1986), and many others, have explored and extended analogous ideas, particularly focusing on robotics. It is possible to make a basic approach to these problems via the Data Rate Theorem, and to include as well regulation and stabilization mechanisms in a unitary construct that must interpenetrate in a similar manner.

Cognition can be described in terms of a sophisticated real-time feedback between interior and exterior, necessarily constrained, as Dretske (1994) has noted, by certain asymptotic limit theorems of probability:

Communication theory can be interpreted as telling one something important about the conditions that are needed for the transmission of information as ordinarily understood, about what it takes for the transmission of semantic information. This has tempted people... to exploit [information theory] in semantic and cognitive studies....

...Unless there is a statistically reliable channel of communication between [a source and a receiver]... no signal can carry semantic information... [thus] the channel over which the [semantic] signal arrives [must satisfy] the appropriate statistical constraints of information theory.

Recent intersection of that theory with the formalisms of real-time feedback systems — control theory — may provide insight into matters of embodied cognition and the parallel synergistic problem of embodied regulation and control. Here, we extend that work and apply the resulting conceptual model toward formally characterizing the unitary structural coupling of brain-body-world. In the process, we will explore dynamic statistical models that can be fitted to data.

The Data-Rate Theorem

The recently-formalized data-rate theorem, a generalization of the classic Bode integral theorem for linear control systems (e.g., Csete & Doyle, 2002; Kitano, 2007; Yu & Mehta, 2010), describes the stability of linear feedback control under data rate constraints (e.g., Mitter, 2001; Minero, Franceschetti, Dey, & Nair, 2009; Nair, Fagnani, Zampieri, & Evans, 2007; Sahai, 2004; Sahai & Mitter, 2006; Tatikonda & Mitter, 2004; You & Xie, 2013). Given a noise-free data link between a discrete linear plant and its controller, unstable modes can be stabilized only if the feedback data rate $\mathcal{H}$ is greater than the rate of 'topological information' generated by the unstable system. For the simplest incarnation, if the linear matrix equation of the plant is of the form $x_{t+1} = \mathbf{A}x_t + \ldots$, where x_t is the n-dimensional state vector at time t, then the necessary condition for stabilizability is

$$\mathcal{H} > \log[|det\mathbf{A}^u|] \quad (1)$$

where det is the determinant and $\mathbf{A}^u$ is the decoupled unstable component of $\mathbf{A}$, i.e., the part having eigenvalues $\geqslant 1$.

The essential matter is that there is a critical positive data rate below which there does not exist any quantization and control scheme able to stabilize an unstable (linear) feedback system.

This result, and its variations, are as fundamental as the Shannon Coding and Source Coding Theorems, and the Rate Distortion Theorem (Ash, 1990; Cover & Thomas, 2006; Khinchin, 1957).