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Outline of a general theory of behavior and brain coordination

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ABSTRACT

Much evidence suggests that dynamic laws of neurobehavioral coordination are *sui generis*: they deal with collective properties that are repeatable from one system to another and emerge from microscopic dynamics but may not (even in principle) be deducible from them. Nevertheless, it is useful to try to understand the relationship between different levels while all the time respecting the autonomy of each. We report a program of research that uses the theoretical concepts of coordination dynamics and quantitative measurements of simple, well-defined experimental model systems to explicitly relate neural and behavioral levels of description in human beings. Our approach is both top-down and bottom-up and aims at ending up in the same place: top-down to derive behavioral patterns from neural fields, and bottom-up to generate neural field patterns from bidirectional coupling between astrocytes and neurons. Much progress can be made by recognizing that the two approaches—reductionism and emergentism—are complementary. A key to understanding is to couch the coordination of very different things—from molecules to thoughts—in the common language of coordination dynamics.

1. The neural choreography challenge

New information about the brain is accruing at an astonishing rate at every level—from the molecular to the social. Though tremendous progress has been made, conspicuously lacking is a broad framework of ideas with which to interpret and integrate findings from so many different scales and levels of observation. We are confronted, as a former President of the Society for Neuroscience remarked in recent testimony to the US Congress, with the grand challenge of elucidating ''neural choreography'' (see also Akil, Martone, & Van Essen, 2011). No single focused level of analysis suffices to understand the brain and its disorders. We need to identify the dancers,[1] capture the essence of the dance and uncover how disease disrupts it. The task is daunting: the 'functions' of the brain and of brains interacting with each other, are manifold and nearly countless. Sift through, for example, typical issues of *Neural Networks* or *The Journal of Neuroscience*. The deep problem that won't go away is the relationship between brains and minds, whether individual or collective. Much progress has been made, not least by the efforts of scientists and engineers in the field of neural networks, but an integrative picture is still lacking. The gap between the language of molecules and cellular machinery (genetics, neuroscience) and the language of mind and its various disorders (cognitive science, neurology and psychiatry) seems very large indeed and is fast widening. There is a belief that things will work out in the end, but at the moment it remains just that—a belief.

Might we take a different tack on the problem? Our intent here is to outline a conceptual and empirical framework ('a general theory') that aims to provide insight into how different levels of organization across multiple space and time scales are connected. Though it certainly relies upon them, on offer here is not a detailed model of neurons and neural machinery supporting hypothesized processes involved in cognition and behavior. The central idea is that all such processes—regardless of the level of description—depend on coordination and the different forms it takes. Our approach is to identify the dynamic laws of coordination and reveal their mechanistic realizations level by level, using both a top-down and a bottom-up approach. By ascribing physiological meaning to the parameters and mathematical expressions in a (computationally implemented) phenomenological theory we aim to bridge the gap between behavioral phenomena and their neural underpinnings.

2. Connecting the micro and the macro

Twenty-five years ago, around the time that the journal *Neural Networks* was being founded, we reported empirical and

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[1] And to pursue the metaphor, there are dancers inside the dancer, like Russian dolls.

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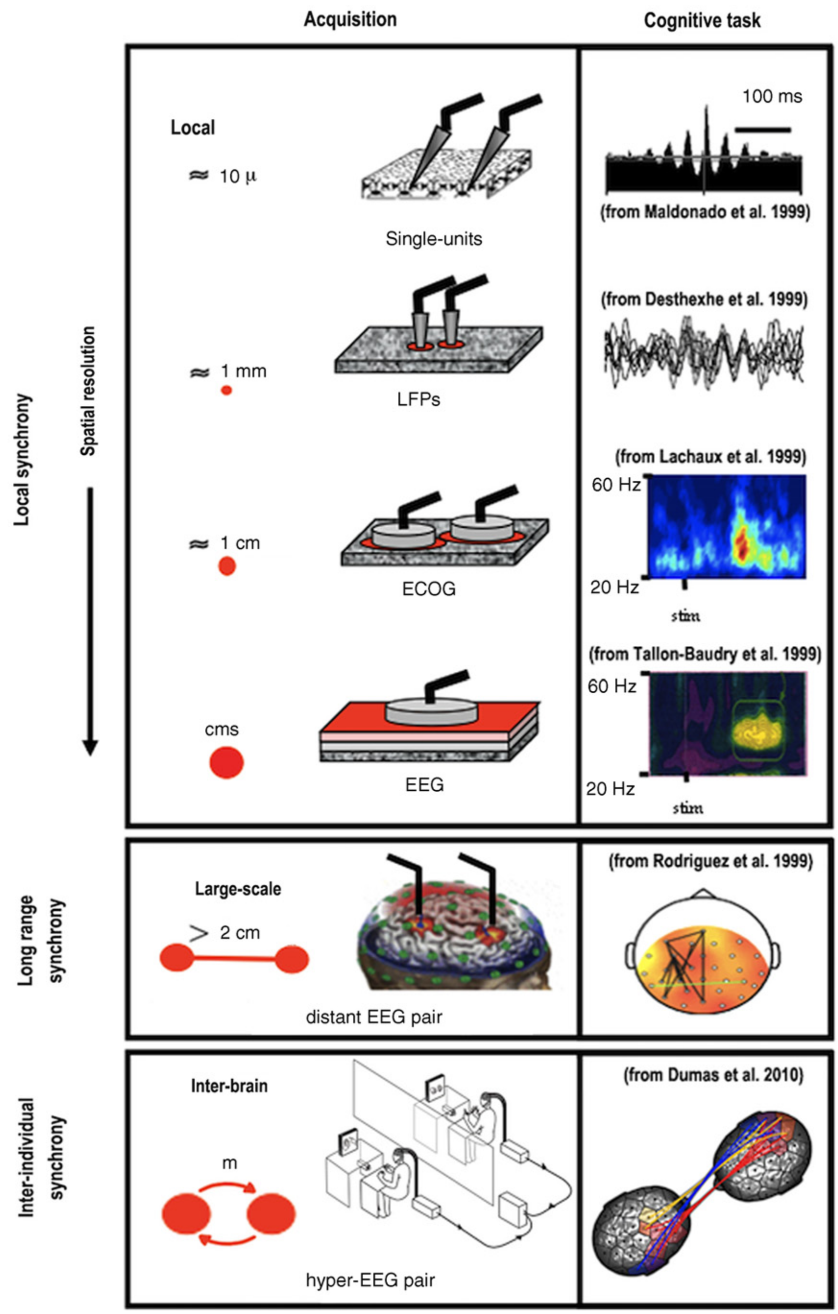

Fig. 1. Multiple scales of the nervous system using synchrony as an example of neural coordination. Notice the right column corresponds to effects that are observed in various task settings. The 'local scale' has three levels of analysis: single units, local field potentials (LFP) and ECOG/EEG. At larger scales, long range synchrony may be observed between distant brain regions. At the inter-individual scale, neural synchronization emerges between different brains through reciprocal social interaction.
Source: Adapted from Varela et al. (2001).

theoretical results demonstrating that coordinated patterns of human behavior could be explained using the concepts of self-organization in open, nonequilibrium systems, particularly synergetics (Haken, 1977/1983) and the mathematical tools of nonlinear dynamics (Schöner & Kelso, 1988, for a review). We intimated then that similar principles are likely to be present also in elementary neural circuits called central pattern generators. In the intervening period, the evidence for mulitifunctionality in neural circuitry viewed as multistable dynamical systems is overwhelming (Briggman & Kristan, 2008, Prinz, Bucher, & Marder, 2004; see also Grillner & Graybiel, 2006). Moreover, in the last 30 years principles of self-organization have been shown to govern patterns of coordination (a) within a moving limb and between moving limbs; (b) between the articulators during speech production; (c) between limb movements and tactile, visual and auditory stimuli; (d) between people interacting with each other spontaneously or intentionally; (e) between humans and avatars; (f) between humans and other species, as in riding a horse; and (g) within and between the neural substrates that underlie the coupled behavior of human beings as measured using MEG, EEG and fMRI (Fuchs & Jirsa, 2008; Kelso, 1995, 2009, for reviews). How might these phenomena be understood?

There are strong hints that laws of coordination in neurobehavioral systems are generic and deal with collective properties that emerge from microscopic dynamics, but how to understand such emergent phenomena has proven difficult in the extreme. An argument can be made that such laws are truly *sui generis* and that it may not be possible, even in principle, to deduce higher