A Roadmap to Computational Social Neuroscience

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Abstract. To complement experimental efforts toward understanding human social interactions at both neural and behavioral levels, two computational approaches are presented: (1) a fully parameterizable mathematical model of a social partner, the Human Dynamic Clamp which, by virtue of experimentally controlled interactions with real people, allows for emergent behaviors to be studied; and (2) a multiscale neurocomputational model of social behavior that enables exploration of social self-organization at all levels—from neuronal patterns to people interacting with each other. These complementary frameworks and the cross product of their analysis aim at understanding the fundamental principles governing social behavior.

Keywords: social coordination, HKB, spatiotemporal patterns, coordination dynamics

1 Introduction

In proposing a framework for Computational Social Neuroscience, we are guided by the broader enterprise of Computational Neuroscience, an essential ingredient in understanding brain and behavior. The complementary approach of empirical science affords only a partial view of the system's spatiotemporal organization, observed dynamics being restricted to certain domains of phase space. The comprehensive organization of the system's dynamics is concealed, as is the continuity between qualitatively distinct states (e.g. normal and pathological regimes; distinct behavioral or cognitive states). Dynamical modeling of the brain provides a simplified but more extensive view: it stretches the boundaries of empirical data, exposes continuity between qualitatively different regimes, shows the paths leading from one regime to another, and attempts to reveal the entire parameter space toward the ultimate goal of discovering the fundamental laws governing brain and behavior [1],[2].

As a branch of neuroscience concerned with the coordination of behavior between individuals, social neuroscience is well positioned to benefit from computational approaches. In the following, we outline some unique opportunities that have arisen recently. After presenting the theoretical foundations, we review a hybrid framework where human subjects, by virtue of mutual coupling, interact with mathematically-modeled partners in real-time [3]. This framework, called the Human Dynamic Clamp (HDC), [4],[5], leads to the study of brain and behavior in the human subject, behavior and parameters in the virtual partner, and coordination dynamics of both (Fig. 1 center). Next we discuss entirely computational efforts (Fig. 1 right), in which two or more people are modeled, in order to shed light on the behavioral and neural underpinnings of social interactions. Social behavior can be formalized at multiple scales: neural, behavioral and social [6]. In such multiscale modeling efforts, surrogate subjects are represented as mathematical models of self-sustained oscillations describing activity in neural areas and body parts that interact through (e.g. visual) perception of partners' behavior. Finally, we discuss how to articulate meaningfully the efforts of experiments and models to gain a more comprehensive understanding of basic social interactions.

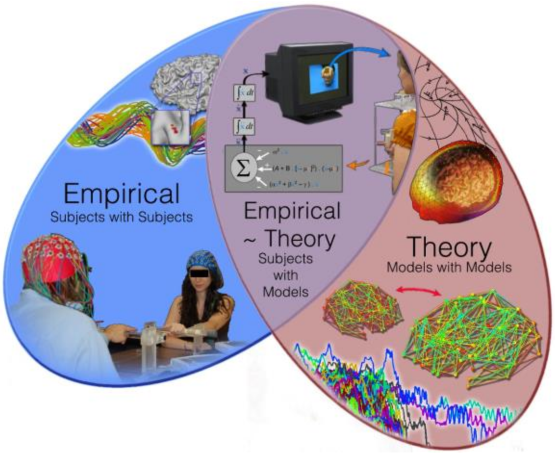

Fig. 1. Complementarities between experimental and computational social neuroscience.

2 Theoretical Framework and Mathematical Models

The Haken-Kelso-Bunz model [7] is a system of (nonlinearly) coupled nonlinear oscillators that reproduces essential properties of biological coordination (e.g. different forms of phase synchrony, instability, phase transitions, etc.) whose empirical study led to the further discovery of a host of complex phenomena such as critical slowing, fluctuation enhancement, hysteresis, etc. (see [8] for recent review). In HKB, symmetry plays a big role in restricting dynamical possibilities. The extended version of HKB [9] broke symmetry, thereby acknowledging that oscillators can have different intrinsic dynamics. With this extension it became possible to handle coordination of dissimilar elements. Thus, heterogeneity -a difficulty in many computational efforts, especially in systems with large number of elements - was returned to scientific reach [10],[11]. The model's broken symmetry led to new insight into the phenomenon of metastability which has been proposed as a fundamental principle of brain and behavior ([1],[10],[12]-[19]). A further step in the development of HKB was to create the mathematical conditions for discrete behaviors to arise from the continuous dynamics of the system's self-sustained oscillators, the so-called 'Excitator' model [20]. Although it seems intuitive that continuous behavior is the result of a juxtaposition of discrete actions, nature may go the other way around, using basic building blocks with self-sustained dynamics such as central pattern generators to produce discrete behaviors [21],[22]. Further, adaptive coordination was developed by making previously fixed parameters of the coordination equations (e.g. intrinsic frequency) dynamic and time-dependent, giving rise to an augmented behavioral repertoire in the model [4]. Finally, directed coordination was developed to bias the collective behavior toward the "intention" of one of the oscillators, leading it to become a "teacher" to the other [4], to the effect that HDC's human partners could learn new patterns of collective behavior [23]. Over the course of three decades, the overall framework of coordination dynamics has been built based upon experimental observations. The fact that its predictions have been confirmed at behavioral, neural and social levels (e.g. [24]-[27],[4]-[6] for social evidence) renders coordination dynamics a viable foundation for computational social neuroscience.

3 The Human Dynamic Clamp (HDC)

In the hybrid experimental~modeling paradigm of the Human Dynamic Clamp, a human and its mathematical mirror, a Virtual Partner, are reciprocally coupled via the empirically-verified HKB equations of coordination dynamics [4],[5]. Virtual Partners perceive the movement of human partners through sensors, and humans through viewing the output of the computational model in real-time as its motion is rendered as an animated image on a computer screen. Both the intrinsic dynamics of the Virtual Partner and its coupling to the human can be manipulated in real-time. Human and virtual partners are provided with coordination tasks to jointly accomplish and behavioral coordination is studied as in human-human experiments. Importantly, while affording comparison with real social contexts, HDC allows experimental manipulations that are not easily accessible when studying the interaction between humans (e.g. turn-taking transitions). HDC has already led to the discovery of novel coordination behaviors and behavioral transitions not seen before in standard paradigms, presumably because it allows broader expanses of parameter space to be explored and manipulated [5]. Starting from equations for virtual partners' rhythmic motion of a single body part at a single frequency, and varying the model-equations according to the successive models mentioned in section 2, it was possible to put the Human Dynamic on a path to ever more complex social behaviors [4]. In the principled design of HDC, each new task context does not constitute an independent implementation of a single target behavior. Rather, HDC builds human behavior from its more primitive foundations with the explicit idea of developing multi-functionality as an emergent property. By constructing each new mathematical model as a generalization of a previous version, a more complete behavioral repertoire is possible foretelling, perhaps, a future when the Human Dynamic Clamp will be able to deal with any arbitrary human behavior.

4 Multilevel and Multiscale Modeling of Social Behavior

Integrating multiple levels of description into a single dynamical account is a longstanding feature of coordination dynamics [2],[6],[10],[27]. Fully neurocomputational models of social behavior require at least three levels: the neural, the behavioral and the social. Early work connected two of them, the behavioral and the social [5], while leaving the neural scale implicit (though the neural level is profoundly entwined in the mathematical description of social coordination behavior, it did not receive its own distinct equations). The neural level was explicitly integrated in [28] in a model that related the dynamics of social behavior with neural dynamics in a realistic architecture of brain areas (including interbrain structural symmetries). Realism was achieved by fingerprinting actual human brains: neural areas were obtained by anatomical brain atlas and connections from diffusion tensor imaging. Brain areas were mapped as neural masses to self-sustained oscillators coupled non-linearly with their phases. The coupling was neural within brain and informational between brains. Results assessed how the anatomical connectivity of the human brain enhances similarities of the neural dynamics and facilitates the creation of sensorimotor coupling between individuals [28].

Each of the three aforementioned levels might organize themselves at multiple spatiotemporal scales, for instance, spatially, the nervous system is known to organize at micro- meso- and macro-scales. A forthcoming step is to expand the spatial scales of the Dumas et al. [29] model nervous system, with the addition of spatial scales at microscopic and mesoscopic levels as e.g., in [29],[30]. The social “Model-of-Models” will then be set to interact, simulating tasks by manipulating relevant inter-subject couplings between (oculo-) motor, perceptual and emotional brain areas. The model leads to two investigative lines: (1) how a “clamped” coordination behavior pattern explains multiscale neural dynamics (local oscillations or neuromarkers, network activity within and between brains, to be compared to empirical evidence [24],[31]); and (2) how empirically-motivated neural activity patterns (neuromarkers of social behavior, clamped) originate various forms of social interactions. As before, the partners’ degree of similarity can be fully controlled, e.g. with pairs of people composed of virtual twins or with pairs whose connectomes have greater differentiation. Such a research program would allow to explore countless developmental, clinical and functional questions such as infant~adult, patient~therapist, expert~novice interactions.

5 Interplay with Experimental Approaches and Concluding Remarks

Computational approaches are powerful scientific tools, yet they are only as valuable as they are capable of two-way conversation with experimental approaches. In the preceding, we illustrated how empirical data inform the design of adequate computational models, built from meaningful variables to explain key phenomena [3]. In return, models point to yet-undiscovered phenomena for empirical approaches to confirm or not. The Human Dynamic Clamp is a major upgrade in throughput for this two-way real-time conversation providing direct knowledge of parameter ranges under investigation. Another notable advantage of models lies with their ability to relate multiple organizational levels and multiple spatiotemporal scales. For instance with respect to temporal scales, models are not only essential but in some cases may be the only methods we have. Already there are hints that social behavior has relevant manifestations at slower time scales (e.g. mood changes that may span months to years, particularly salient in pathology). Yet, experimental windows typically exclude continuous study of phenomena that exist on longer time scales. Coordination Dynamics predicts that the slower dynamics springs from and couples with faster time scales, a prediction that can be verified in models. Similarly, since no human brain imaging method currently transcends all spatial levels of description [32], models have an important role to play in bridging the gaps between the micro- and the macro-scale of neural dynamics. These are key challenges for the theoretically-grounded framework of Computational Social Neuroscience outlined in this overview.

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