Dynamic Field Theory: Conceptual Foundations and Applications in the Cognitive and Developmental Sciences

Gregor Schöner (gregor.schoener@rub.de), Christian Faubel (christian.faubel@rub.de)
Institut für Neuroinformatik, Ruhr-Universität Bochum, 44780 Bochum, Germany

Vanessa Simmering (simmering@wisc.edu)
Department of Psychology, University of Wisconsin — Madison
1025 W. Johnson Street Madison, WI 53706-1969 USA

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Background of the tutorial

For the last 20 years, the concepts of Dynamical Systems Theory have been influential in the way psychologists, cognitive scientists, and neuroscientists think about sensori-motor behavior and embodied cognition. These concepts have had a particularly strong impact in developmental science, changing the way questions are asked, experiments are designed, and theoretical models are formulated. The initial emphasis on motor behavior was expanded when autonomous robotics was used as a tool to explore how the approach scaled to increasing behavioral and environmentel complexity. In this transition from an account of sensori-motor behavior to an account for cognition, a key step was to address how the concept of representation could be given meaning with Dynamical Systems thinking. Dynamical Field Theory (DFT) provided an answer to this question, offering a framework for thinking about representation-in-the-moment that is firmly grounded in both Dynamical Systems thinking and neurophysiology. Dynamic Neural Fields are formalizations of how neural populations represent the continuous dimensions that characterize perceptual features, movements, and cognitive decisions. Neural fields evolve dynamically under the influence of inputs as well as strong neuronal interaction, generating elementary forms of cognition through dynamical instabilities. The concepts of DFT establish links between brain and behavior, helping to define experimental paradigms in which behavioral signatures of specific neural mechanisms can be observed. These paradigms can be modelled with Dynamic Neural Fields, deriving testable predictions and providing quantitative accounts of behavior.

Although Dynamical Systems thinking has had impact even when used at the level of metaphor, the full strength of these concepts is brought to bear when they are operationalized through mathematical modeling and quantitative analysis. This is particularly true of DFT, in which the classification of instabilities enables the systematic analysis of embodied cognitive systems. One obstacle for researchers wishing to use DFT has been that the mathematical and technical skills required at this operational level do not form part of the standard repertoire of cognitive scientists. The goal of this tutorial is, therefore, to provide the training and tools to overcome this obstacle.

We will provide a systematic introduction to the central concepts of DFT and their grounding in both Dynamical Systems concepts and neurophysiology. We will discuss the concrete mathematical implementation of these concepts in Dynamic Neural Field models, giving all needed background and providing participants with some hands-on experience using interactive simulators in Matlab. We will review robotic implementations to make the ideas concrete and demonstrable. Finally, we will take participants through a number of selected, exemplary case studies in which the concepts and associated models have been used to ask questions about elementary forms of embodied cognition and their development.

The interactive simulators will be available at the tutorial. We will also give participants access to generic production-level simulators of Dynamic Field Models that can be expaned by participants to simulate and evaluate Dynamic Field Models that they may develop in their own work.

Target audience

The tutorial will introduce participants to the area. No specific prior knowledge of the mathematics of dynamical systems models or neural networks is required as the mathematical and conceptual foundations will be provided during the tutorial. An interest in formal approaches to cognition is an advantage. Because dynamical systems tools are not standard in Cognitive science, researchers with prior experience in connectionist or computational modeling may be interested in the tutorial as well.

Outline of the tutorial

1. Conceptual foundations of Dynamical Systems Thinking and Dynamical Field Theory (DFT): Embodied and situated cognition; Stability as a necessary property of embodied cognitive processes; Distributions of population representation as the basis of spatially and temporally continuous neural representations; *Duration: 45 minutes*

2. Dynamical Systems Tutorial: Concept of dynamical system; Attractors and stability; Input tracking; Detection, selection, and memory instabilities in discrete neuronal dynamics; Dynamical Fields and the basic instabilities: detection, selection, memory, boost-driven detection; Learning dynamics; Categorial vs. graded mode of operation; Practical implementation of DFT in simulators; Interactive simulation with possibility for students to follow along

on their own computers; Illustration of the ideas through robotic implementations; *Duration: 90 minutes*

3. Case studies of using DFT to understand embodied cognition and its development: The detection, selection, memory and boost-driven detection instability are all experienced in perseverative reaching in infants; Emergence of cognitive function when environment changes in unspecific ways; Metric working memory in children and adults; Discrimination and change detection; Precision hypothesis as a developmental perspective on embodied cognition; *Duration: 445 minutes followed by 90 minutes, separated by the lunch break*

4. Toward higher cognition: Multi-layer Dynamical Fields; Architectures of Dynamical Fields; Multi-dimensional Dynamic Fields and real-time association; Solving the binding problem; Coordinate transformations; *Duration: 45 minutes*

5. Scaling Dynamical Field Theory: Robotic implementations of complex Dynamical Field architectures; *Duration: 45 minutes*

Suggested Readings

(available at http://www.uiowa.edu/∼icdls/dft/dft-publications.html)

1. Schöner, G. (2008): Dynamical Systems Approaches to Cognition. In: The Cambridge Handbook of Computational Psychology, Ron Sun, (ed.), Cambridge University Press, pages 101-126.

2. Johnson, J.S., Spencer, J.P. & Schöner, G. (2008). Moving to higher ground: The dynamic field theory and the dynamics of visual cognition. *New Ideas in Psychology* **26**: 227-251

3. Simmering, V.R., Schutte, A.R., & Spencer, J.P. (2008). Generalizing the dynamic field theory of spatial working memory across real and developmental time scales. *Brain Research* **1202**: 68-86.

4. Spencer, J.P., Simmering, V.R., Schutte, A.R., & Schöner, G. (2007). What does theoretical neuroscience have to offer the study of behavioral development? Insights from a dynamic field theory of spatial cognition. In J. Plumert & J.P. Spencer (Eds) The Emerging Spatial Mind. Oxford University Press, pages 320-361.

5. Schöner, G.: Development as Change of System Dynamics: Stability, Instabilty, and Emergence. In: Toward a New Grand Theory of Development? Connectionism and Dynamic Systems Theory Re-Considered, J.P. Spencer, M. Thomas, & J. McClelland (Eds.), Oxford University Press (August 2009)

Computer support

Participants who bring lab-tops with Matlab installed (student version is sufficient) will be able to follow demonstrations by actively working with the simulator during the lectures.

Lecturers

Gregor Schöner is a Professor of Neurocomputing and holds the Chair for Theoretical Biology at the Institut für Neuroinformatik of the Ruhr-Universität Bochum, Germany. He received his PhD in 1985 in theoretical physics at the University of Stuttgart under the supervision of Hermann Haken, the founder of the field of synergetics. After several years as a Visiting Scientist and Research Associate at Haskins Laboratories and the Center for Complex Systems at Florida Atlantic University, Dr. Schöner became a Group Leader for Theoretical Neuroscience at the Institut für Neuroinformatik. In 1994, he became Directeur de Recherche at the Centre de Recherche en Neurosciences Cognitives of the CNRS in Marseilles, France, returning to Bochum, Germany in 2001 to accept the Chair for Theoretical Biology. Dr. Schöner is considered one of the world's experts on dynamic systems theory within the fields of Psychology and Cognitive Science and was among the first to apply Dynamic Neural Fields to the study of cognition and autonomous robotic behavior. He will teach the conceptual and mathematical tutorials (numbers 1, 2, and 4 above).

Vanessa Simmering is an Assistant Professor at the Department of Psychology of the University of Wisconsin — Madison. She obtained her PhD in Psychology under the supervision of John Spencer at the University of Iowa with work on spatial working memory, discrimination, and category formation. In her published work and her current research agenda she combines experimental and modeling approaches structured by the concepts of Dynamical Field Theory. She will lecture on the case studies of using DFT concepts to design, analyze and interpret experiments on elementary forms of cognition and their development (number 3 above).

Christian Faubel is a postdoc at the Institut für Neuroinformatik of the Ruhr-Universität Bochum, Germany. He received his PhD from the Department of Electrical Engineering and Information Technology af the same university with projects in which he used the concepts of DFT to design computer vision systems that autonomously learn to recognize objects from one to five views of each object. He has also been responsible for the design of dynamical systems architectures for the anthropomorphic robot CORA, which interacts which human users. He will lecture about how DFT architectures scale for real-world computer vision tasks (number 5 above).