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Using Dynamic Field Theory to extend the embodiment stance toward higher cognition

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ABSTRACT

The embodiment stance emphasizes that cognitive processes unfold continuously in time, are constantly linked to the sensory and motor surfaces, and adapt through learning and development. Dynamic Field Theory (DFT) is a neurally based set of concepts that has turned out to be useful for understanding how cognition emerges in an embodied and situated system. We explore how the embodiment stance may be extended beyond those forms of cognition that are closest to sensorimotor processes. The core elements of DFT are dynamic neural fields (DNFs), patterns of activation defined over different kinds of spaces. These may include retinal space and visual feature spaces, spaces spanned by movement parameters such as movement direction and amplitude, or abstract spaces like the ordinal axis along which sequences unfold. Instances of representation that stand for perceptual objects, motor plans, or action intentions are peaks of activation in the DNFs. We show how such peaks may arise from input and are stabilized by intra-field interaction. Given a neural mechanism for instantiation, the neuronal couplings between DNFs implement cognitive operations. We illustrate how these mechanisms can be used to enable architectures of dynamic neural fields to perform cognitive functions such as acquiring and updating scene representations, using grounded spatial language, and generating sequences of actions. Implementing these DFT models in autonomous robots demonstrates how these cognitive functions can be enacted in embodied, situated systems.

1. Introduction

One way to approach embodied cognition is to observe that there is a lot of cognition in such seemingly mundane activities as soccer playing. Although soccer playing may commonly be thought of as a motor skill, perception is a critical component as well. Players must quickly acquire an understanding of the scene, and segment and categorize objects such as the ball, the goal posts, line markings, other players, and the umpire. Every player must track these objects when either the objects or the player move. Good scene understanding, including a perception of space that affords planning, is key to successfully driving the game ahead. Although it has been said that the world is its own best model, to effectively orient within the scene and direct gaze back to relevant objects, players must have a scene representation or spatial map that can be used even when the exact position or orientation of the player has changed since the last updating of the map from sensory information.

The motor aspects of soccer playing go well beyond conventional motor control. Actions must be initiated or aborted, action goals must be selected, distractors – suppressed. Sensorimotor decisions must be continuously

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updated, as objects move and view-points change. Updating may also take place at higher levels, such as when switching back from an offensive to a defensive strategy immediately after losing control of the ball.

Finally, soccer playing always involves learning, which takes place whenever an individual plays. From soccer game to soccer game, there is an obvious developmental trajectory, with a general increase in competence as experience with such open games accumulates. More subtly, soccer playing involves a lot of background knowledge about such things as how hard to hit the ball, how hard to tackle another player, or how slippery the ground may be. Such background knowledge (Searle, 2004) is difficult to capture, but it is a clear reminder that the cognition that happens in soccer is not the processing of arbitrary information. Instead, this form of cognition happens in a specific context, to which players are particularly adapted by training or even by evolution and which provides supportive structure for the tasks handled by the Central Nervous System during a game of soccer.

The recognition that cognitive processes take place in such embodied and situated settings has led to important new thinking (reviewed, for instance, by Anderson (2003); Ballard, Hayhoe, Pook, and Rao (1997); Brooks (1990)). The new ideas include the insight that cognitive processes are based on active perception, are linkable to the sensory and motor surfaces, can be updated at any time, and are sensitive to situational and behavioral context (Schneegans & Schöner, 2008). These new ideas have resonated with a developmental approach to cognition that dates back to Piaget (Piaget, 1952) and emphasizes the sensorimotor origins of cognition (Thelen & Smith, 1994).

But is all cognition embodied? Not all cognition involves bodily motion or even the processing of sensory information (Riegler, 2002). Are the constraints that arise from the discovery of embodied cognition universally shared by all cognitive processes? Are all cognitive processes linkable to sensory and motor surfaces; do all cognitive processes unfold in continuous time, capable of updating their contents at any moment based on new incoming information; are all cognitive processes sensitive to context and open to learning? The *embodiment hypothesis* is that these questions must be answered in the affirmative! According to the embodiment hypothesis there is no particular boundary below which cognition is potentially embodied, beyond which these constraints no longer apply and “real” cognition begins. The more we know about the neural basis of cognition, the more clearly we see a true continuum of neural processing from the sensorimotor domain to the highest form of cognition (Bar, 2011). Early sensory and motor areas are also actively involved in acts of higher cognition (Jeannerod & Decety, 1995; Kosslyn, Thompson, & Ganis, 2006). And skills of a seemingly sensorimotor nature require the intervention of relatively high-level cognitive control (Koechlin, Ody, & Kouneiher, 2003).

If the embodiment hypothesis is true, how may we go about understanding cognition? How do we make the embodiment program, the investigation of cognition on the basis of the embodiment constraints, concrete and operational? To us a critical step is to develop a constructive, process-oriented theory that enables the modeling of concrete acts of embodied cognition. We believe that such a theory must be based on neuronal principles, that will make it compatible with the constraints imposed on information processing in the Central Nervous System.

Dynamic Field Theory (DFT) grew out of this research agenda. Its beginnings lay in the sensorimotor domain (Erlhagen & Schöner, 2002; Kopecz & Schöner, 1995) and the development of early cognition (Thelen, Schöner, Scheier, & Smith, 2001). The key ideas of DFT are: (1) Patterns of neural activation evolve in time as described by neural dynamics that captures the evolution of the activity of populations of neurons in continuous time. (2) The neural activation patterns are defined over continuous spaces, which describe sensory and motor states and abstract from the discrete sampling of these spaces by individual neurons. (3) Localized peaks of activation are units of representation, which indicate through high levels of activation the presence of a well-defined value along the dimensions of the activation fields. That value is indexed by the location of the peak within the neural field. (4) Neural interaction within the activation fields is structured so that localized peaks are stable stationary solutions, or attractors, in the neural dynamics.

The spatio-temporal continuity of the neural activation fields in DFT is critical to establishing stability as an operational concept. Stability is the resistance of solutions to change induced by variations of sensory input or by noise. Thus, stability requires a metric, a way to express what it means to be close to a state and to converge in time toward a state after a perturbation has occurred. Whenever a neural process is part of a feedback loop, stability is a critical property without which the neural process will not have a reliable function. In order to have an impact on the down-stream neural structures or motor systems, a neural state needs to persist over a macroscopic period of time despite neural and sensory noise, as well as continual changes in the sensory input. Stability is the basis for representation in DFT and the key to countering the anti-representationalist approach to embodied cognition (Chemero, 2009).

In DFT, a set of instabilities controls how peaks as attractor states may be created or may disappear. These instabilities give rise to three elementary cognitive acts (Schneegans & Schöner, 2008): (1) The detection instability creates a peak in response to input. (2) The selection instability controls which among multiple stimulated values of a dimension is stably selected. (3) The memory instability separates a regime in which peaks persist once the inducing input is removed from a regime in which peaks are only stable in the presence of such input. These instabilities have been used to account for signatures of early cognition such as sensorimotor decision making (Trappenberg, Dorris, Munoz, & Klein, 2001; Wilimzig, Schneider, & Schöner, 2006), spatial cognition (Simmering, Schutte, & Spencer, 2008) and its development (Schutte & Spencer, 2002), change detection (Johnson, Spencer, & Schöner, 2008), and visual search (Fix, Vitay, & Rougier, 2007, pp. 170–188). For the link to the underlying neuronal mechanisms see, for instance, Coombes (2005).

In this review we explore how the language of DFT enables us to extend the embodiment stance toward higher