Neural dynamics for behavioral organization of an embodied agent

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A great amount of the actions we execute during our daily life is organized in sequences. Even a simple task such as grasping an object implies a sequence of different behaviors: first, the target objects must be found, involving the visual system, making saccades or turning your head; second, the location of the object has to be assessed and the grasping movement planned and prepared accordingly. Only then can the hand be brought to the target object and the actual grasp, parametrized by the geometry of the object, can be performed. The ease with which humans perform such behaviors is astounding considering the complexity of the task. The behaviors not only imply complex transformations between different reference frames, but also rely on several parameters, shaping the dynamics of different motor systems. Furthermore, they rely on constantly changing sensory input that needs to be perceived, its parameters estimated and reliably represented to affect the behavior of the agent. Consequently, the stability of the states of the cognitive system, which affect the agent during a particular behavior, is a major requirement.

The continuous flow of action observable in the physical world may be understood as the result of sequential activation of more low-level, reusable *elementary behaviors* (EB) in the cognitive system. This idea has, for instance, been fruitful in the design of systems controlling the behavior of artificial robotic agents [1].

The core question of our work deals with the way EBs may be organized sequentially in time. Several mechanisms are possibly responsible for this and, within a complete cognitive system, most certainly interact. The first is the serial order mechanism, in which the resulting sequence is arbitrary and fixed. This mechanism is at play during routine or over-learned sequences and is involved in habit formation [2,3]. Another sequencing mechanism is *behavioral organization*, which is based on the fact that a great amount of behavioral sequences adhere to certain rules regarding the sequentiality of the actions. For instance, when grasping an object on a table, the hand must be opened before the reaching movement is completed. By enforcing such constraints on the sequentiality of certain behaviors, a vast number of possible but meaningless sequences can be eliminated. In fact, in some cases the correct order of behaviors within a complex task can be realized by such constraints alone. Here, we focus on this exact case by introducing a neural-dynamic representation of an EB framed in Dynamic Field Theory (DFT) [4] and show rule-like sequencing based on constraints enforced between those EBs.

In DFT, the states of a cognitive system are represented as activity distributions defined over dimensions relevant for the behavior of the agent. These can be visual features, motor parameters, or more abstract cognitive dimensions, such as the location of an object in an allocentric representation of the environment.

Within our model, an EB consists of two interacting elements, an *intention* and a *condition of satisfaction* (CoS), both of which are represented by stable states of dynamic neural fields (DNF). The *intention field* of an EB is directly coupled to the underlying perceptual and motor system. Thus, its activation results in observable behavior. The *CoS field* receives excitatory activation from the intention field and matches the desired outcome of the EB against the current sensory input. Activation in this DNF inhibits and effectively turns off the intention field, denoting the successful completion of the EB.

The sequential activation of such EBs emerges from task-specific behavioral constraints and particular inputs from the environment. We define three such constraints between pairs of EBs: a *precondition*, a *suppression*, and a *competition constraint*. All of these constraints are modeled using dynamic neural nodes, which can be activated and deactivated depending on the particular task.

Our neural-dynamic model is able to organize EBs sequentially in time based on behavioral constraints while constantly dealing with noisy, fluctuating sensory input as well as unforeseen changes in the environment. We demonstrate this by implementing the model on the humanoid robot NAO in a table-top scenario. The behavioral organization allows for autonomous object-oriented arm movements in a real-world environment shared with an interacting human user.

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