A Hybrid Cognitive System with a Physiological Substrate

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Extending a computational cognitive system with a computational model of physiology is a useful way to simulate and study the interactions between physiology and cognition, and to understand how the embodiment of cognition modulates intelligent behavior. Though there has been previous work in extending these systems to include moderators of cognition meant to provide a high-level representation of ways changes related to physiology can affect human intelligent behavior, no work had previously been done on integrating systematic computational models of physiology. I developed a novel hybrid architecture (ACT-R/Φ) that extends the ACT-R architecture with an integrative model and simulation of human physiology. This architecture allows us to develop more realistic and tractable intelligent agents that are dynamically modulated by bottom-up physiological processes over time. With this hybrid system, we can better simulate and understand how the embodiment of cognition can result-in and affect intelligent action and behavior.

1. INTRODUCTION

Extending a computational cognitive architecture and a computational model of physiology is a beneficial way to simulate and study the interactions between physiology and cognition, and to understand how the embodiment of cognition modulates intelligent behavior. Computational process models of human behavior provide predictions on how changes in information, both internal and external, may affect a given behavior. Computational models of cognition allow us to better understand how intelligent behavior may be affected by differences in information and the consequences of the interaction between, and integration of, several psychological processes during this intelligent behavior. These models allow us to study how behavior may change over-time, and explore how performance may be improved when interacting with other systems. Developing such agents and models using a computational cognitive architecture gives a developer the opportunity to describe and operationalize information processing with an integrated set of mechanisms. Thus, over-time, agents become more realistic, tractable, and accumulate knowledge with a common foundation.

With systematic computational models of physiology, we can simulate the effects of various changes in physiology on whole integrated systems; we can see the temporal, spatial, and functional pervasiveness of changes. These models also allow a better understanding of how extreme physiological states may modulate systematic behavior in ways that may be difficult or unethical to use in human experimentation. A modeler can better predict what will happen to a physiological system given a particular extreme, rare state.

Despite the advances in developing computational models on the cognitive and physiological levels, few computational architectures have been developed that provide representations for both cognitive and physiological systems. If we are to better understand how and why we learn and make the decisions we do, it will be important to understand the interactions of these systems and how this embodiment of cognition modulates observable rational and irrational behavior.

2. A NOVEL HYBRID COMPUTATIONAL ARCHITECTURE

Recognizing that a gap existed in the research pertaining to realistic simulations of human behavior, I developed a novel hybrid computational architecture (ACT-R/Φ) that can be used to model and simulate human behavior on physiological, affective, and cognitive levels [Dancy 2013]. This is the first system to integrate a model and simulation of physiology with a cognitive architecture. The architecture has a foundation from existing work in cognitive science and AI [e.g., Anderson 2007; Newell 1990], affective neuroscience [e.g., Panksepp 1998], and computational physiology [Hester et al. 2011]. I connected the ACT-R cognitive architecture [Anderson 2007] to the HumMod physiological model and simulation system [Hester, Brown, Husband, Iliescu, Pruett, Summers and Coleman 2011], and used a theoretical framework from affective neuroscience to facilitate and operationalize many of these connections (see, Panksepp et al. 2011 and Wright and Panksepp 2012, for explanation of some individual parts of the framework and, Panksepp 1998, for a treatise on the theoretical framework as a whole).

This new computational architecture can be used to not only understand the interactions between physiological, affective, and cognitive systems, but also understand how these interactions affect behavior during the operation of systems. The original ACT-R architecture has been used in several ways to better describe and predict human-system interactions [e.g., Salvucci 2009; St. Amant et al. 2007]. More recent efforts have built-upon this work by looking at the effects of fatigue on cognition and human-system performance [e.g., Gunzelmann et al. 2011]. However, none of these approaches directly consider the effects of physiology or emotion, though the case for the importance of physiological and affective modulators has been made previously [e.g., Hudlicka and Mcneese 2002; Picard 2000].

Nonetheless, prior to development of models that describe and quantify human-computer interaction, development of models that simulate the fundamental interactions between cognitive and physiological processes that modulate intelligent behavior is important. It will be important to base the behavior exhibited by these physiological and affective HCI process models on the underlying interactions that modulate memory, learning, and decision-making processes.

3. MULTILEVEL COMPUTATIONAL PROCESS MODELS OF HUMAN BEHAVIOR

I've developed process models that operate within the ACT-R/Φ architecture, but have different aspects of behavior modulated by architecture while completing tasks [Dancy and Kaulakis 2013; Dancy et al. In Press]. These computational agents exhibit bottom-up changes of cognitive systems due to interaction with physiological and affective systems.

Though there has been previous work that has studied the cognitive effects of stress and how to model these effects using a cognitive architecture [e.g., Ritter et al. 2009], but what happens when we consider dynamic architectural parameters? Physiological systems are normally in a constant dynamic state due to homeostatic, and potentially allostatic, change due to interactions with both the environment and with affective, cognitive systems. Some of what is traditionally considered "noise" may also be explained as change in an underlying physiological state. I developed a computational process model of the effects of stress on a serial subtraction task. The model connects physiology to cognition by simulating some effects of peripheral physiology on cognitive performance over-time [Dancy, Ritter, Berry and Klein In Press].

In the stressed serial subtraction model, physiological changes (due to stress) cause a dynamic memory noise. Thus, performance changes for the model depending on its physiological state at a given point in time. The simulated physiological system also does not reset after completing consecutive blocks of subtraction, instead physiology continues to non-linearly change across time from the first block of the task to the final block. The model allows us to better study how early stress in a task affects not only the behavior during that particular block, but also performance later in later blocks. We can simulate and predict the prevalence of physiological effects on performance over time.

I used the dynamic declarative memory noise values from this model to better understand the range of performance exhibited over the course of the task. Additional simulations that used these noise values with static parameter versions of the model gave us an idea of how well the dynamic memory noise model was performing at any given point in time during the task. This method potentially allows the prediction of what physiological and affective states result-in optimal performance during tasks. Thus, it becomes clearer how physiological adaptations can result in flexible intelligent behavior.

I've also developed ACT-R/Φ agents that simulate cognitive and affective processing during a decision-making task (a modified version of the Iowa Gambling Task, IGT). These agents use the cognitive and affective systems in the ACT-R/Φ architecture, as well as the perceptual/motor system to complete the IGT. During the simulation, the agent communicates with open-source task software that has also been used to gather empirical data on how certain subliminal visual stimuli affects learning, decision-making, and physiology during the task. This is one of the few computational cognitive agents, or process models, that provide an account for changes in physiological and affective systems, and also provide an account for the interactions between different types of learning and memory (e.g., reinforcement learning, and associative declarative learning) used during decision-making. Understanding how interactions between cognitive, affective/emotional, and physiological systems affect the way we learn and make the decisions we do is fundamental to understanding human interactions and behavior.

4. FUTURE WORK

The work I've done with the ACT-R/Φ architecture, computational process models, and empirical work are steps towards the goal of understanding the relation between intelligent behavior and action, and cognitive, affective, and physiological interactions. Intelligent agents and computational process models will remain an important complement to theoretical and empirical work. In developing these simulations it will also be important to optimize the implementations in software so that more agents can be run in parallel, in less time; this will be especially important as heavier cognitive agents are used to understand social network communication and decision-making [e.g., Zhao et al. accepted].

Understanding limitations a priori (cognitive, affective, or physiological) will continue to be important for explaining both dysfunctional and functional intelligent behavior when interacting with systems. Using a unified architecture or framework will make the knowledge gained from experimentation more tractable and allow the knowledge to accumulate with a common foundation. In the future, I plan to build on my previous work and continue to develop the ACT-R/Φ architecture from a theoretical and software perspective so that more interesting and useful intelligent agents may be developed; this includes identifying data and tasks that would benefit from a multi-level perspective and developing models of these tasks and data, and optimizing software implementations so that it may run faster, is more robust, and can interact with a wider range of external systems. I will also develop computational models and agents using other theories and systems to complement the work done with ACT-R/Φ; this will allow me to more robustly study how interactions between physiological, affective, and cognitive systems change the way we think and interact with the environment.

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