MASTERARBEIT | MASTER'S THESIS

Titel | Title

Investigating the Mind-Body Interfaces in ACT-R/Phi, an Extended Cognitive Architecture Integrating a Circuit Theory of Affect and Utilizing a Physiology Simulation

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Contents

Abstract

The ACT-R/Phi (Dancy, 2021) cognitive architecture extends the seminal cognitive architecture ACT-R (Anderson, 2007) with the HumMod (Hester et al., 2011) physiology simulation. The purpose of this extension, is to model the influence of physiological processes on cognitive processes. In ACT-R/Phi, the influence of physiology on cognition is modeled based on the theory of primary affect (Panksepp and Biven, 2012). In this thesis I shine the cognitive science student's flashlight on this interface between body and mind. For this purpose I engage with the ACT-R/Phi cognitive architecture to develop an understanding of the implemented interface between body and mind. Informed by this practical exercise, I contextualize ACT-R/Phi with theoretical discussions around the mind-body problem with a specific focus on the contributions of cognitive science (4E cognition), neuroscience, and philosophy.

By implementing an interface between ACT-R and HumMod, Dancy shows the practical feasibility and opens up a path for exploring interfaces between physiology – emotion – cognition. While ACT-R/Phi has not been widely used outside of Dancy's work, the influence of this modified cognitive architecture is reflected in the discussions around the role of emotion in the "Common Model of Cognition" in particular. The role of physiology is mentioned centrally in the proposed emotion module of the "Common Model of Cognition".

In this thesis I sketch out the potential contributions and limitations of the ACT-R/Phi approach to the realm of cognitive modeling in general and the discussions around adding Emotion to the Common Model of Cognition in particular. My investigations into the overlapping borderlands of the realms of cognitive science, philosophy, neuroscience, and affective science provide additional motivation and reasons to integrate the role of the body in general and the (neuro)physiology of the brain in particular when it comes to modeling cognition and emotion. This thesis serves as a potential fundament for further

inquiry into the principled modeling of the relationship between body and mind, as well as emotion and cognition.

Zusammenfassung

Die Kognitive Architektur ACT-R/Phi (Dancy, 2021) erweitert die wegweisende Kognitive Architektur ACT-R (Anderson, 2007) um die Physiologie-Simulation HumMod (Hester et al., 2011). Der Zweck dieser Erweiterung ist es, die Einflüsse physiologischer Prozesse auf kognitive Prozesse zu modellieren. In ACT-R/Phi wird der Einfluss physiologischer Prozesse anhand des Konzeptes von "Primary Affect" modelliert (Panksepp and Biven, 2012). In dieser Masterarbeit beleuchte ich diese Schnittstelle zwischen Körper und Geist aus der Perspektive des Studenten der Kognitionswissenschaft. Für diesen Zweck setze ich mich theoretisch und praktisch mit der Kognitiven Architektur ACT-R/Phi außeinander um ein Verständnis für die implementierte Schnittstelle zwischen Körper und Geist zu gewinnen. Im Anschluss dieser praktischen Übung kontextualisiere ich ACT-R/Phi mit theoretischen Diskussionen rund um das "mind-body problem" (Leib-Seele-Problem) mit besoderem Fokus auf die Beiträge aus der Kognitionswissenschaft (4E-Kognition), den Neurowissenschaften, und der Philosophie.

Durch die Implementierung einer Schnittstelle zwischen ACT-R und HumMod hat Dancy die praktische Machbarkeit einer Schnittstelle zwischen Physiologie – Emotion – Kognition demonstiert und somit einen wichtigen Grundstein für weitere Arbeit in dem Bereich gelegt. Obwohl ACT-R/Phi außerhalb der Arbeiten von Dancy nicht verwendet wird, hat der Vorstoß von Dancy die Diskussion rund um das Modellieren von physiologischen Einflüssen auf Kognition geprägt und weitere Forschung in diesem Bereich inspiriert. Die Rolle von Physiologie ist im vorgeschlagenen Emotionsmodul des "Common Model of Cognition" an zentraler Stelle erwähnt.

In dieser Arbeit skizziere ich die potenziellen Beiträge und Grenzen des ACT-R/Phi-Ansatzes für den Bereich der kognitiven Modellierung im Allgemeinen und die Diskussionen um die Erweiterung des "Common Model of Cognition" um Emotionen im Besonderen. Meine Untersuchungen in den sich überschneidenden Grenzbereichen von Kognitionswissenschaft, Philosophie, Neurowissenschaft, und affektiver Wissenschaft liefern zusätzliche Anreize um die Rolle des Körpers im Allgemeinen und der (Neuro-)Physiologie des Gehirns im Besonderen zu integrieren, wenn es um die Modellierung von Kognition und Emotion geht. Diese Masterarbeit dient als potenzielle Grundlage für weitere Arbeiten zur systematischen Modellierung der Beziehung zwischen Körper und Geist (Leib und Seele) sowie Emotion und Kognition.

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Chapter 1

Introduction

The aim of this master's thesis is to aim the cognitive science student's flashlight on how the relation between the "Mind" and the "Body" as represented in the hybrid cognitive architecture ACT-R/Φ[1] (Dancy, 2014, 2021). ACT-R/Phi was developed by Christopher Lee Dancy II as part of his dissertation work at the Pennsylvania State University [2].

ACT-R/Phi extends the seminal cognitive architecture ACT-R with a human physiology simulation (HumMod, Hester et al. (2011)) and an operationalization of a circuit theory of affect and emotion. In order to do so, I will first introduce my personal background and professional motivation to write this thesis: I will make clear what kind of perspective you can expect when reading the subsequent chapters. Secondly, I will introduce the topic, aim and scope of the thesis. Third, I will introduce the methods I used. In this master's thesis I shine my flashlight on a very specific attempt of modeling the relation between "Body" and "Mind". In this thesis, the "Body" is HumMod (Hester et al., 2011), a mathematical simulation of integrative human physiology and the "Mind" is ACT-R (Anderson, 2007), a seminal cognitive architecture. My flashlight is also rather specific as I write this thesis in the Middle European interdisciplinary master's programme in Cognitive Science (MEi:CogSci) at the University of Vienna.

In the upcoming sections of this chapter I will lay out my personal background and

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[1] Dancy introduces and refers to ACT-R/Phi as ACT-R/Φ. I will refer to ACT-R/Φ as ACT-R/Phi throughout this thesis for reasons of easier search and accessibility. ACT-R/Phi is additionally referred to as: ACT-RΦ, ACT-R/ϕ, ACT-R Phi, or ACT-R/Phi.

[2] As of the writing of this thesis, Dancy is Harold and Inge Marcus Industrial and Manufacturing Career Development Associate Professor at Penn State, where he heads the "The Human in Computing and Cognition Lab" (THiCC Lab).

motivation, the topic, aim and scope; as well as the methods of my thesis. I will conclude with an overview of places, persons (and institutions) I deem relevant for this thesis and point towards important definitions. The further thesis will be structured as follows: First, I will set the stage by introducing ACT-R/Phi – the work of Christopher Dancy tying together ACT-R and HumMod. Second, I will engage with ACT-R/Phi from a users perspective and will put my magnifying glass on the interface between HumMod and ACT-R. For this purpose, I trace the path of the physiology variables – as simulated by HumMod – through ACT-R/Phi to illustrate how physiology variables influence ACT-R/Phi and secondly, how ACT-R/Phi influences physiology variables in HumMod. The purpose of this is to illustrate the concrete implementation of ACT-R/Phi in order to contextualize the implementation with the theoretical considerations. Third, I will take a step back and introduce the Mind-Body Problem and lay out arguments why taking the body seriously in cognitive modeling might be useful. I will do this by introducing the embodied approach to cognition. Fourth, I will continue by discussing the role of affect in ACT-R/Phi and introduce recent and historically significant discussions around the relation between emotion and cognition. I will conclude the thesis by reflecting on the reception and future of ACT-R/Phi, assessing the work I did (and did not do), reflecting on the process I went through and close with my final thoughts related to ACT-R/Phi.

1.1 Personal Motivation and Background: Why this Thesis?

My primary motivation to conduct this thesis is twofold. Firstly, I want to understand ACT-R/Phi beyond the theoretical description by engaging with the ACT-R/Phi artifact. Secondly, I want to contextualize ACT-R/Phi within my understanding of cognitive science which is heavily influenced by the 4E[3] approach(es) to cognition in general and embodiment in particular.

In order to provide more context as to who is writing this thesis, I will lay out secondary reasons for me conducting this thesis. I have been personally invested in the topic of how our biological reality and felt experience interact. I believe my initial interest was spiked during my adolescence, when I was struggling to understand the health situation of a close

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[3] 4E stands for embodied, embedded, enactive, and extended.

relative. Various conditions had this person gain significant weight and I lacked sympathy and understanding. During my Civil Service at a hospital (but also some time before that) I embarked on a journey with this person to “take control” of our metabolisms. Over months of discussions and action, we changed our dietary intake and shared our subjective experiences. It was the first time when I personally tried to very carefully understand how different dietary choices impacted my subjective well-being and energy levels. Over ten years later, I feel somewhat more competent in understanding how what I put into my body and how I feel in the hours and days after relate. At the same time I feel clueless: Many more factors play a role in determining how I feel any given day than the food I consumed the day(s) before. We are a complex organisms living in a mostly symbiotic relationship with a whole host of other organisms that contribute (causally? constitutively?) to our conscious and sub-conscious experience.

During my Bachelor at the Vienna University of Economics and Business, I learned about ways in which *economists* try to explain human behavior. From a micro(economic) perspective: looking at smaller scale things from individuals to firms. From a macro(economic) perspective: looking at global patterns. Unsatisfied with approaches starting out with rational agents, I found interest in *behavioral economics*, where researchers depart from the general assumption of rational agents and explicitly address all those cases, in which humans do not behave rationally. It was around this time when I stumbled upon approaches trying to explain human behavior from the perspective of *behavioral biology.* I was fascinated by the idea that there might be a way to find out how genes determine behavior[4].

After some time away from university, I started to volunteer in the Neuropsychopharmacology & Biopsychology Unit (NBU) at the University of Vienna, where I helped with participant recruitment (which eventually became the basis for my current day job) and, where I helped administer testosterone gel onto the chests of study participants in an effort to unravel the effect of testosterone on decision making and risk taking behavior[5].

It was during this stint that I became aware of the MEi:CogSci programme that I am wrapping up now. I was influenced by many classes, thoughts and ideas during my masters: I try to synthesize these in this thesis and try to make as explicit as possible where my thinking comes from. Equally, there are many interesting classes I never took

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[4] I do not believe this to be the case.

[5] I (unsuccessfully) tried to participate in the experiment before I applied as a volunteer.

or concepts that did not latch on. I will also try to make these explicit, even if this is a difficult task. As a third category, there are concepts and ideas that might be relevant to this thesis and that I do know of but that I simply do not have the time to integrate into this work properly. I will utilize footnotes to point towards these thoughts and resources.

Over the last decade, I have slowly started to re-discover my physical body: As a child, I spent many hours playing video games. I have often neglected my body in these hours, ignoring cold feet, sacrificing posture and other things. After some time – and very much so in the years during my master's in cognitive science – I have started to (re-)engage with my body in various ways: running, cycling, (body)weight exercises, heat (sauna) and cold (water) exposure, meditation, ... to name most. On a good day I feel fitter and stronger than I ever felt before: physically and mentally.

My relationship with food is another one that has been evolving over time and I am very much aware of the multiple functions food has. Of course it serves our physiological needs but I am acutely aware of the high importance of the social role of food. Trying to feel the effects of food, exercise of the body, and exercise of the mind on my phenomenal experience has been a pet project but anyone who engages in these tasks and tries to measure their impact on ones state of mind knows that this is not an easy task. I have been very interested in following developments of all kind of physiological tracking devices but never actually used one myself. The culmination of my masters in this thesis fits into this narrative excellently: I try to assess the value of simulating the human body and the human mind in a computer.

Towards the end and initially perhaps an afterthought, the role of emotion (or affect) plays an important part in this thesis as a necessary concept in between bodily states and mental states. Personally, I am still on a journey trying to learn to map the felt states of my body to emotional states that I can use in exchange with other humans. Often neglected – especially in males – learning to name emotions is crucial in making sense of the world.

Important things happened during the Training Embodied Critical Thinking seminar, where I first properly understood the concepts of phenomenology, microphenomenology and neurophenomenology. Taking seriously the subjective experience of an individual is something that intuitively makes plenty of sense. Doing it in a structured manner, utilizing e.g. Claire Petitmengins stlye of microphenomenological interview can – in my opinion – be an extremely powerful resource.

Another important milestone was the Groningen Spring School on Cognitive Modeling where I made my first serious encounter with ACT-R and at the end, felt enabeled and confident to embark on this master thesis topic.

Just as I learn that there is value in listening to my body, I think building a cognitive architecture that can "listen" to its body is an interesting step forward. I will argue that this is grounded in recent research into the neuroscience of affect/emotion, philosophical inquiries regarding the body and brain/mind – including the enactivist tradition in cognitive science – as well as "bottom up" research in (cognitive) robotics[6].

1.2 Contributions of this Thesis

In this work, I shine my flashlight at a tiny subsection of this topic: namely, the role of the extension of the ACT-R Cognitive Architecture by modules that connect it to the HumMod physiology simulation.

My theoretical contribution is the contextualization of ACT-R/Phi especially with concern to its relation to research in cognitive science and affective science. My aim is to take what I would mostly consider an applied & engineering project from Christopher L. Dancy and find its place inside of philosophical discussions around the mind-body problem. I re-trace the steps that Dancy took throughout his thesis, in order to explicate theoretical assumptions and contextualize them. My aim with this exercise relate the theoretical foundation and the practical implementation. In particular, I take a look at the theory of affect that Dancy decided to use as the basis for his additional ACT-R/Phi modules.

I understand the work of Dancy as exploratory in nature as emphasized throughout his dissertation. For example he states that equations used to create the interface between HumMod and ACT-R are in no shape or form *the right equations* (Dancy, 2014, p. 68). Nevertheless, the equations implemented and the assumptions they are based on can be taken as a good first step.

Based on my motivation and background I will now list my research questions, provide an overview of the structure and content of the thesis, set the scope of the thesis, deliver

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[6] See e.g. "From Animals to Animats" for a long standing tradition of seeking inspiration in biological systems – down to the implementation level – for building robots capable of intelligent behavior.

a brief statement why I conduct this research now and finally, provide a disclaimer.

1.2.1 Research Questions

RQ1 How is the gap between the physiological and the cognitive (body-mind) bridged in ACT-R/Phi using affective science?

RQ2 What are the (causally influencing and constituting) relationships between the physiological state of the body (milieu) and the (neuro)physiological state of the brain, and of the (neuro)physiological state of the brain and cognitive functions and performance that are covered in ACT-R/Phi?

RQ3 Has Dancy's work ACT-R/Phi achieved the (theoretical and engineering) goals he set out for? i.e.: Is it theoretically sound and practically usable?

RQ4 What is the scientific significance of ACT-R/Phi (i.e.: How is it being used and referenced)? How does this "embodied affective" cognitive architecture relate to 4E cognition, and ongoing development in cognitive science? What are potential and actual key scientific contributions of expanding cognitive architectures with affect and a simulation of physiology; which (new) challenges result from this work (or have become clearer through it)?

1.2.2 Structure and Overview

This thesis is structured as follows:

1. Chapter 2: ACT-R/Phi: Theoretical

   Investigating interfaces between physiology and cognitive architectures from the perspective of a cognitive science student

   - Special focus on the relation between the body, physiology, the mind, cognitive architectures and cognitive science
   - And the role of affective science as a means of connecting the physiological and cognitive.

2. Chapter 3: ACT-R/Phi: Practical
   Working with the cognitive architecture ACT-R/Phi based on a general understanding of them from the perspective of an “informed user”

3. Chapter 4: The Mind and The Body: MEi:CogSci and Philosophy
   Theoretical considerations about the nature of the Mind Body relation and how it relates to ACT-R/Phi in particular and Cognitive Architectures and Computer Simulation Models in general

4. Chapter 5: The Mind and The Body: Physiology – Affect – Cognition
   Theoretical considerations about the nature of the relation between physiology, affect, emotion and cognition and how they relates to ACT-R/Phi in particular and Cognitive Architectures and Computer Simulation Models in general

5. Chapter 6: Discussion – Assessment – Reflection
   Discussion of the reception and potential applications of ACT-R/Phi in particular. Discussion of the general issues and problems with the approach of ACT-R/Phi in particular and cognitive architectures in general. Assessment of what I managed and did not manage to achieve. Reflection on the process of writing this thesis.

1.2.3 Scope of this Thesis

- Investigating Interfaces between Physiology and Cognitive Architectures from the perspective of a cognitive science student
  - Special focus on the relation between physiology, the mind, cognitive architectures and cognitive science
  - ... and the role of affective science as a means of connecting the physiological and cognitive.
- Working with the cognitive architecture ACT-R/Phi based on a general understanding from the perspective of an “informed user”
- Working with the physiology simulation HumMod based on a general understanding of the principles of the simulation and the systems it attempts to simulate from the perspective of an “informed user”

1.2.4 Out of Scope

I have a strong urge to go ahead and try to relate *everything* I know to the topic of this thesis and explicate it on the following pages. Just as with cognitive architectures, if there are too many free floating bits you sacrifice something. In the interest of staying concise and not trying to fit everything in, I will restrain myself to keeping to the topic at hand.[7]

To be precise, the following topics are explicitly outside of the scope of this thesis:

- Altering ("fixing") ACT-R/Phi, developing alternative designs[8];
- Extended philosophical contextualization of ACT-R/Phi;
- Relating this work to the work on "Symbol Grounding";
- Relating the concept of *primary metaphors* to notions of primary affect/core-affect. For *primary metaphors* see the doctoral dissertation of Joseph Edward Grady (1997), supervised by George Lakoff;

1.2.5 Why ACT-R/Phi, Why Now?

ACT-R/Phi was developed over ten years ago. The first publication towards ACT-R/Phi was published in 2012 (Dancy et al., 2012). This begs the legitimate question why I write this thesis in 2024. I do so because as of today and to my knowledge, ACT-R/Phi continues to be the only cognitive architecture that integrates a model of a body. Because of this, ACT-R/Phi lends itself to be analyzed as an example for just that: a cognitive architecture with a simulated body. In addition, the discussion around the Common Model of Cognition prominently features the question, which role emotion should (or should not) play – hence the lack of a consensus on the topic so far. A recent proposal by Rosenbloom et al. (2024) suggests an emotion module connected to a physiology simulation without going into details. Engaging with ACT-R/Phi provides an excellent entry point into discussions regarding the role of emotion and physiology in cognitive architectures.

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[7] I will use footnotes to point towards topics that appear related to the questions at hand but that are outside of the scope of this thesis.

[8] I will however pick up the general topic in a constructive manner, as Chris Dancy invites us to do in his thesis.

1.2.6 Disclaimer

This is my master's thesis. I have a diverse background including computer science, economics and cognitive science, with a broad range of interests. I worked in a hospital, in customer service, private companies, and state funded companies. I fixed many computers and enjoy making and drinking coffee and tea, and finding out more about myself by experimenting with various diets, fasting and other "health fads". I travelled the world a bit. I grew up bilingual in a multicultural family, classrooms and work environments. At the time of this writing, I consider my strengths to lie in the ability to relate between various areas, driven by a wish to "connect" and see the "whole picture".

This thesis, while written with the full intent to adhere to scientific standards, is also the product of me and my environment and guided but also limited by it. I take full responsibility for all the errors in this thesis. As anyone who has ever written something, deciding when to stop writing will stop the words on paper to develop, but not the ideas behind them. I am looking forward to seeing the ideas I tried to capture on paper develop further as the years pass.

1.3 Methods

1.3.1 Desk Research

I applied various methods of desk research – some inspired by Abbott (2014) and some inspired by my practical experience in bibliography analysis (citation analysis). I browsed (mainly) digital racks. I browsed through the works of individual researchers. I conducted citation analysis to identify works referring to core works for my thesis. In particular, I searched for academic publications that directly referenced work written by Christopher L. Dancy.

I screened the proceedings of conferences that I identified as relevant for my thesis:

- International Conference on Affective Computing and Intelligent Interaction and Workshops, ACII
- Agents
- Biologically Inspired Cognitive Architectures, BICA

- Cognition and Artificial Life
- Advances in Cognitive Systems
- Annual Meeting of the Cognitive Science Society, CogSci
- From Animals to Animats, International Conference on Simulation of Adaptive Behavior
- International Conference on Cognitive Modeling, ICCM
- Conference on Social Computing, Behavioral-Cultural Modeling & Prediction and Behavior Representation in Modeling and Simulation, SPB BRiMS

1.3.2 Applied Research

I worked with ACT-R/Phi (Dancy, 2021). ACT-R/Phi consists of two software components: the ACT-R Cognitive Architecture (Anderson, 2007) and the HumMod Physiology Simulation (Hester et al., 2011). Dancy extended the ACT-R Cognitive Architecture with additional modules that enable communication between HumMod and ACT-R. I explicitly focused on the ACT-R/Phi modules that implement the interface between ACT-R and HumMod.

The aim of working with these simulation tools was to gain an applied understanding of working with cognitive architectures in general and with and ACT-R/Phi in particular as well as to familiarize myself with ACT-R/Phi to an extent that enables me to explain the interface between mind and body implemented in it in detail and relate the artefact to my theoretical considerations.

The majority of the work I conducted with regard to ACT-R/Phi was to analyze the program code and run various test models in ACT-R/Phi while modifying HumMod variables. I did this in order to understand and utilize ACT-R/Phi beyond mere theoretical understanding that I obtained by studying the literature. I did this with the aim of understanding how the interface between ACT-R/Phi and HumMod is practically implemented beyond the explanations provided in publications.

To demonstrate my practical understanding of ACT-R/Phi, I modified the Zbrodoff task – a task from the ACT-R tutorial to run with ACT-R/Phi and documented the necessary modifications to do so.

I documented the necessary steps to set up ACT-R/Phi in Windows 10 in Appendix A.

1.3.3 Reflection

In an attempt to take Varela et al. (2016) seriously I came up with my own way of laying my path down in walking. For me this meant continuously checking in with my subjective experience while working on this thesis and making time and space to actively *think* about my thesis. For this I employed methods I learned at a series of seminars of the Training Embodied Critical Thinking (TECT) Erasmus+ training program[9]. I primarily focused on checking in with my felt experience while engaged with the topics of my thesis cognitively.

I employed a variety of methods for this, including regular meditation practice (228 sessions logged in a meditation app), active talks about my thesis (roughly 100 talks with my supervisor, discussions with colleagues, friends and family) and learning to listen to my body when engaged with ideas that I was not able to talk about yet.

When I officially started my work on this thesis in the Fall of 2022 I dedicated 90 of 625 hours[10] to engage in "reflective" activities in an effort to escape the "me sitting in front of the computer theorizing about the physical and phenomenal reality of human existence" from a purely theoretical perspective.

1.4 ACT-R/Phi: A Cognitive Architecture with Physiology and (Primary) Affect

ACT-R/Phi is "A cognitive architecture with physiology and affect" (Dancy, 2013, p. iii). It is an extension of the ACT-R cognitive architecture developed by John R. Anderson

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[9] The TECT programme concluded in 2023 and is succeeded by Training in Embodied Critical Thinking and Understanding (TECTU), available in at the original TECT homepage: `https://www.trainingect.com/` (accessed 2024-08-30).

[10] This thesis is "worth" 25 ECTS credits (European Credit Transfer and Accumulation System). Each ECTS credit is considered to be the equivalent of 25–30 hours of work, which results in 625 hours of workload on the lower end to complete the learning outcomes associated with writing a masters thesis. The actual time to achieve the required learning outcomes varies for each individual student European Commission, Directorate-General for Education, Youth, Sport and Culture (2015).

at Carnegie Mellon University. The theoretical framework is most recently documented in Anderson (2007) and the technical implementation in Bothell (2023).

ACT-R/Phi consists of four additional ACT-R modules. It also includes and requires a modified version of the HumMod physiology simulation by Hester et al. (2011) (included with ACT-R/Phi). ACT-R/Phi is the result of Christopher L. Dancy II's doctoral dissertation at Pennsylvania State University under the Supervision of Frank Ritter.

ACT-R/Phi provides the red thread for this thesis. My aim is to ground my discussion in the ACT-R/Phi cognitive architecture. Before diving into the theoretical considerations of ACT-R/Phi I will next provide some background and introduce some of the persons – and their institutions – who made research into cognitive architectures possible in the first place.

1.4.1 Setting the Stage, Providing the Context

The term setting refers to the sum of environmental factors that define the set of possible outcomes. Just like no Olympic swimmer can emerge from a town without an adequate training facility, the same holds true for academic endeavours. The people Christopher Dancy worked with during his dissertation directly and by extension, are arguably the most prominent researchers in the history of cognitive architectures. The list includes – by extension – the creators of the first AI program, Allen Newell and Herbert A. Simon.

In Figure 1.1, I lay out part of the professional environment in which ACT-R/Phi was created. The graphic depicts institutions, persons and key theories/software implementation of these theories.

The two main institutions of interest with respect to ACT-R/Phi are the Carnegie Mellon University in Pittsburgh (CMU) and the Pennsylvania State University in University Park. Both Institutions are located in Pennsylvania on the East Coast of the United States of America and are a mere 217km apart from each other.

Carnegie Mellon University came into being through the merger of the Carnegie Institute of Technology and the Mellon Institute of Industrial Research. This merger was in part enabled by Herbert A. Simon and Allen Newell and their work on the interface between the psychology and the computer science departments. Simon and Newell established one of the first computer science departments in the world at CMU and Herbert Simon was central for the merger of Carnegie Tech and the Mellon Institute. Within

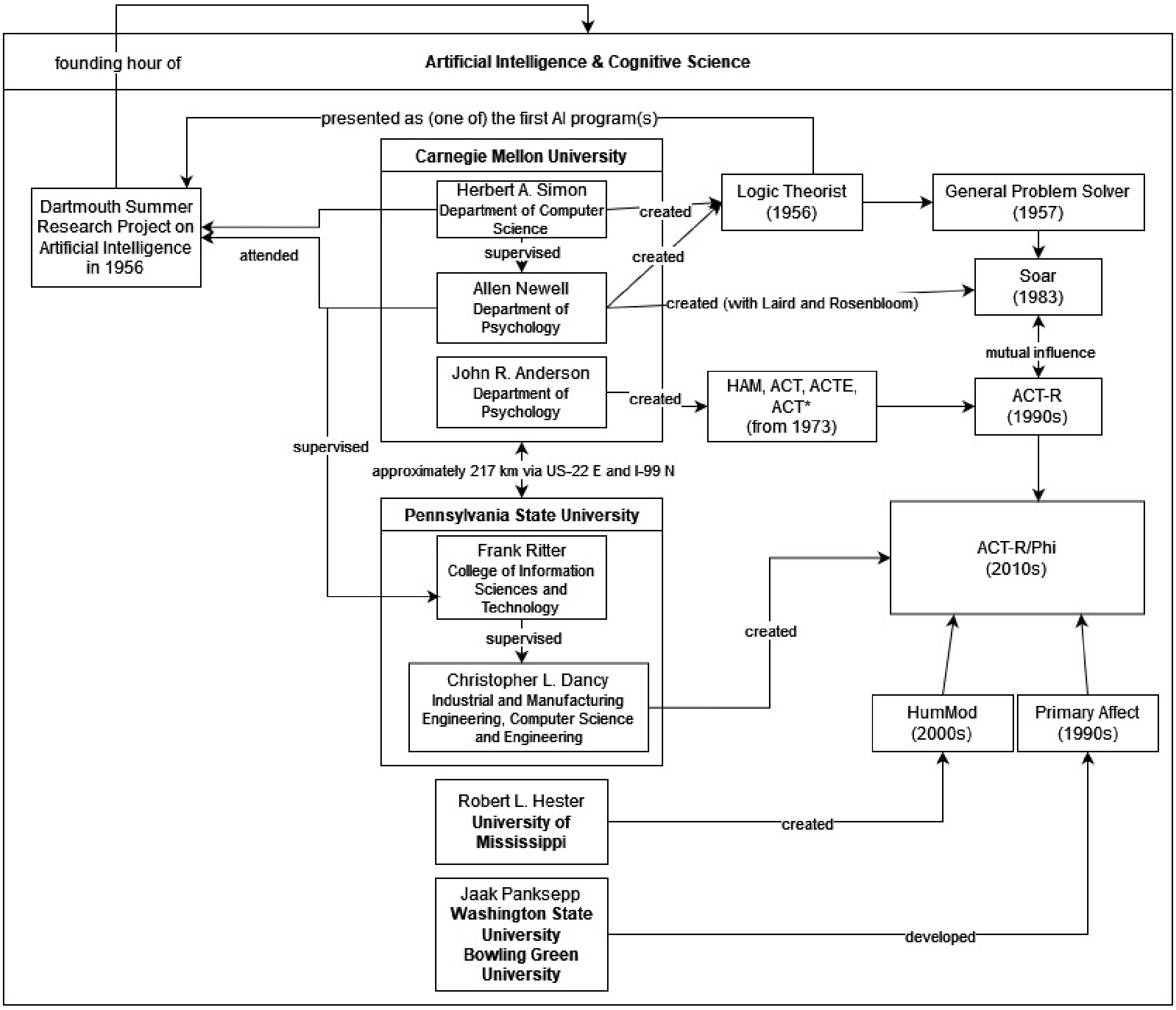

Figure 1.1: An overview of the people and institutions (in)directly involved in the ACT-R/Phi project.

CMU Newell headed the psychology department and Simon headed the computer science department.

In 1955, together with John Clifford (Cliff) Shaw, Simon and Newell developed the first (or second) artificial intelligence program: Logic Theorist (LT)(Crevier, 1993, p. 44). Simon and Newell presented the Logic Theorist at the 1956 Dartmouth Summer Research Project on Artificial Intelligence[11]. After the Logic Theorist, Simon and Newell developed the General Problem Solver in 1957(Crevier, 1993, p. 52f).

Together with his doctoral students, John Laird and Paul Rosenbloom, Allen Newell developed the Soar cognitive architecture: One of the two most widely used cognitive

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[11] They only stayed for a week and their Logic Theorist did not win the hearts of the other participants(Crevier, 1993, p. 49).

architectures to date.

The other most widely used cognitive architecture – ACT-R – was also developed at the Carnegie Mellon University. John R. Anderson started out with a model of human memory (HAM) and gradually expanded this model to become what is now known as ACT-R (Adaptive Control of Thought – Rational[12]). While Anderson did not collaborate with Simon or Newell to my knowledge, it is noteworthy that the two most widely used cognitive architectures were developed at the Carnegie Mellon University.

Another of our protagonists touches the CMU directly: Frank Ritter did his Ph.D. in the Psychology and Computer Science departments supervised by Allen Newell. Ritter agrees that working on Soar between the departments was "Cognitive Heaven"(Ritter, 1993, Acknowledgements). In addition, he was in contact with John R. Anderson who provided "sage advice" whenever needed (ibid.). Thus, one of the links between Soar and ACT-R is in the person of Frank Ritter. Ritter eventually ended up at Pennsylvania State University where he inspired the graduate student Christopher L. Dancy II to look into modeling the influence of physiology on cognitive processes using a cognitive architecture (Dancy, 2014, p. xiv). Essentially, Dancy was able to do his work with the spirits of Allen Newell, Herbert A. Simon, John R. Anderson around him at all times in the person of Frank Ritter.

In addition to the heavy influence of the cognitive architecture scene at CMU, contributions to ACT-R/Phi in form of HumMod – developed by Robert L. Hester at the University of Mississippi Medical Center – based on the first mathematical model of cardiac circulation by Guyton in the 1960s are an essential puzzle piece (HC Simulation, LLC, 2016).

Furthermore, research by Jaak Panksepp and colleagues provided the neuroscientific groundwork that allows us to link peripheral physiology to brain regions (Panksepp, 2004; Panksepp and Biven, 2012).

What I presented here, is the physical, institutional, interpersonal, and intellectual space in which ACT-R/Phi was created. Evidently, this network can be expanded in many ways into the personal support systems of the individuals displayed, into all the many contributors into ACT-R as well as the intellectual environment surrounding the

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[12] The "rational analysis" approach was deemed inadequate for his purposes by Anderson (2007, p. 19), but the -R in ACT-R remains to show that this approach – developed by Herbert A. Simon – did influence the development of ACT-R.

emergence of cognitive architectures in the first place. Just as it could be expanded to include the funding institutions (and persons behind them), enabling the financing of these research endeavours as well as the broader zeitgeist which funded some endeavours – but not others. But just as every model needs boundaries, I believe I covered the most important influences.

It is interesting to reflect on the persons and their environment behind the texts and software that I discuss, and this reflection can provide the necessary supplemental information to better understand the research agenda carried out by these persons across decades.

After having set the stage, I will now introduce the artifact which is at the center for my thesis: The cognitive architecture ACT-R/Phi.

1.5 Definitions

Some useful definitions are provided in the Glossary after the main body of text.

Chapter 2

ACT-R/Phi: Theoretical

In this chapter I introduce the theoretical framework of ACT-R/Phi by explicating the explicit and implicit assumptions inherent to ACT-R/Phi. This chapter lays the groundwork for my subsequent analysis of the software implementation of ACT-R/Phi in Chapter 3, where I will go into a detailed description of the software implementation of the ACT-R/Phi theory.

2.1 The Theoretical Basis of ACT-R/Phi

> *The work in this dissertation uses a predominantly physiological perspective because it gives affective behavior a foundation in human physiology and grounds emotional theory in some known physiological processes.*
>
> —*Christopher L. Dancy, II (2014), p. 3*

Christopher L. Dancy set out developing ACT-R/Phi with an "exploration ... add emotion to a cognitive architecture" and an "[...] intuition that physiological modulation should be represented in a computational system that accounts for affective behaviors" (Dancy, 2014, p. 1). The model to be developed by Dancy should provide a model for interpreting and better understanding diverse results from psychology, physiology and neuroscience in relation to human behavior (ibid., p. 2). In addition, physiology can serve as an additional constraint for a cognitive architecture.

Dancy decides to "ground" his work in evidence from physiological processes. On one hand he relies on the work of Hester et al. (2011) on HumMod for this. On the other hand he relies on the work by Jaak Panksepp, Lucy Biven and colleagues for providing neuroscientific evidence (Panksepp, 2004; Panksepp and Biven, 2012). Dancy thus uses the evidence presented by Panksepp and colleagues on brain circuitry from rodent models and then uses HumMod to simulate physiological variables present in these brain circuits.

By providing an account for physiology, ACT-R/Phi is suited to account for a wider variety of experimental data. It has become increasingly feasible to collect physiological data alongside behavioral / outcome measures in psychological experiments. The proliferation of various tracking devices allow measurement of physical activity, sleep, heart-rate and derivatives of heart-rate measures, body temperature, and blood oxygenation. Minimally-invasive devices allow for example the continuous measurement of blood sugar levels, and further devices are developed and devised that might allow real time monitoring of e.g. hormonal levels. While many of these devices are used for lifestyle, their use in research is constantly pursued and establishing robust measures of emotional states using physiological measures.

In combination with other wearable devices, the amount of data collected form a single individual increases and the necessity to make sense of this data becomes ever more important. With many variables measured, chance correlations with behavioral outcomes increase and spurious correlations are bound to emerge. This increases the necessity to have an understanding in advance for the relationships present in order to devise the correct statistical models for analysis.

One way to achieve this is by creating computational models that simulate the same variables on a computer that are measured in the field. This allows for comparison between measured and simulated data. Creating computational models, such as models in cognitive architectures, requires modelers to make everything they know about the task they are testing in humans explicit. This already is a fantastic way of trying to understand a cognitive phenomenon and consolidating it in one place. The cognitive architecture approach also exposes holes in knowledge that need to be filled. At the same time, creating models in cognitive architectures is constrained by the constraints of the cognitive architectures themselves. Implementing a model in a cognitive architecture poses additional challenges that aren't easily fixed and might expose differences in what is possible in a cognitive architecture and how we theorize about human cognition.

2.1.1 Dancy's Approach

First and foremost, the approach taken by Dancy by creating ACT-R/Phi is a practical approach. My reasoning for this statement is, that Dancy identified the cognitive architecture, theory of affect and emotion and simulations of physiology that were most suited to work for the task he set out to solve: creating a cognitive architecture that would allow us to arrive at a better understanding of the interconnections between physiological and cognitive processes (Dancy, 2014, p. 59f).

Most of the assumptions concerning the nature of cognition, or the relation between body and mind, are results of simply adopting the theoretical stances inherent to the theories that serve as the backbone of ACT-R/Phi.

I will argue that at each of the forks in the road, where Dancy selected one theory over another, he implicitly took a theoretical stance that I will attempt to make explicit here. The aim of this exercise is to set the boundaries within which we can analyze the practical implementation of ACT-R/Phi.

The forks in the road I will discuss are:

1. Selecting ACT-R as the cognitive architecture
2. Selecting Primary Affect as the perspective on emotion/affect
3. Selecting HumMod as the physiological substrate

2.1.2 The Implicit Stance behind choosing ACT-R

Dancy decides to work with ACT-R because he wants to create models that match human experimental data and ACT-R is centered around understanding human behavior (Dancy, 2014, p. 50). From all cognitive architectures, ACT-R has been used most widely (Kotseruba and Tsotsos, 2018, p. 59). ACT-R models usually are concerned with modeling human performance in psychological experiments. By adding a physiology substrate to ACT-R, simulated model physiology can be compared to human physiology. ACT-R is modular and coordinated by a central control system (Anderson, 2007, p. 45). ACT-R/Phi could therefore be created without having to interfere with the original ACT-R implementation, making it a less daunting project than implementing a new cognitive architecture.

In addition to these technical arguments, (Dancy, 2014, p. 50) mentions ACT-R's community base and maturity as factors for choosing to work with ACT-R. Additionally, Frank Ritter – Dancy's PhD supervisor – has expertise in ACT-R (Ritter et al., 2018). Choosing ACT-R was therefore also a smart logistical decision.

Another reason for choosing ACT-R, is that ACT-R is a cognitive architecture where activity within the architecture is associated with brain activity (Dancy, 2014, p. 41). Work by Borst and Anderson (2013) maps the activity of key ACT-R modules to specific brain regions while both humans and cognitive architecture perform the same task. By mapping ACT-R modules to brain areas, researchers can take inspiration in the neurophysiology of these associated brain areas. Based on the neurophysiology of a certain brain area, the physiology characteristic for that brain region – e.g. a certain neurotransmitter – can serve as the basis for modeling the effects of physiological change on performance of the cognitive architecture.

2.1.3 The Implicit Stance behind choosing Primary Affect

In order to make ACT-R/Phi work, Dancy needed a interface between physiology and cognitive processes. Choosing to work with the theory of *primary affect* developed by Jaak Panksepp and colleagues allows Dancy to pursue this path. The work of Panksepp and Biven (2012) develops the theory of primary affect. Primary affect describes how primary (low) level processes (e.g. primary affect) interact with secondary level processes (e.g. memory), to together, influence tertiary (higher) mental processes (Panksepp, 2011, p. 1358). These concepts allows Dancy to draw elegant connections from physiology up to higher mental processes.

By focusing on *primary affect*[1], Dancy can take a relatively sober look at how physiology influence processes like memory, and how memory influences cognitive processes. Dancy explicitly decides for this theory that grounds seeks to relate its findings in brain circuitry. This allows for a straightforward extension of ACT-R (Dancy, 2014, p. 60).

By choosing the primary affect route, Dancy explicitly decides against using a cognitive appraisal theory of emotions[2] as well as against a theory of constructed emotion[3].

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[1] I will return to primary affect in Chapter 5

[2] c.f. The most recent implementation of emotion in Soar I am aware of is based on appraisal theory: Marinier III (2008)

[3] See e.g. Scherer (2022) for a recent overview (from p. 160).

Neither appraisal theory, nor theories of constructed emotion have obvious connections to physiology. In the case of theories of constructed emotion, it might be argued that they stand against the identity theory of mind which states that processes of the mind are identical to processes of the brain (Smart, 2022).

2.1.4 The Implicit Stance behind choosing HumMod

> *"HumMod is a large, multiscale model of human physiology that integrates multiple physiological systems, including the renal, autonomic, endocrine, and cardiovascular systems. [...] HumMod is composed of more than 8,000 independent variables and ∼2,000 parameters and equations"*
>
> *—Pruett et al. (2020, p. 191f)*

HumMod[4] is a mathematical model of human physiology that was developed in the 2000s at the Mississippi Medical Center by Hester et al. (2011). The origins of HumMod can be traced back into the 1960s in which Arthur Guyton started to develop mathematical models of human physiology (HC Simulation, LLC, 2016). Guyton and colleagues expanded this model to cover cardiovascular physiology. Thomas Coleman worked with Arthur Guyton to develop the first computer simulations based on their mathematical models. In the 1980s Coleman developed the HUMAN model which was eventually expanded and resulted in the Windows based Quantitative Circulatory Physiology (QCP). In the 2000s, Robert Hester joined Coleman and together and with colleagues they created HumMod: *"The most complete, mathematical model of human physiology ever created"* (HC Simulation, LLC, 2016).

By deciding to use HumMod as the physiological side of ACT-R/Phi, Dancy chose the most integrated physiology simulation at that time. A recent review by Pruett et al. (2020) suggests that HumMod is still the most comprehensive model of human physiology (p. 191f). The advantage of using HumMod is thus that there are many physiological variables one can choose from and that they are all connected in a principled manner.

While ACT-R/Phi relies on the whole HumMod simulation, it only uses a handful of

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[4] Never specified, possibly Human Model.

the over 8000 physiological variables available. An important detail to be considered is the fact that HumMod is a physiology simulation and not a neurophysiology simulation. The work in and around ACT-R has not only been inspired by, but also grounded in research in cognitive neuroscience, as evidenced by the research linking ACT-R module activation and brain area activation Borst and Anderson (2013). Thus, relying on a physiology simulation keeps us a bit shy from the neurophysiology. A potential downside to HumMod is that it does not model brain neurophysiology in a way that would allow connecting a virtual brain region to a ACT-R module directly.

2.1.5 The Implicit Philosophical Stance

Even though ACT-R/Phi is referred to in the context of the Standard Model of the Mind[5] needing a body (Dancy and Ritter, 2017), the texts around ACT-R/Phi are not concerned with discussions around Embodiment or Enactivism – which I will discuss in Chapter 4. Rather the need for a body is argued based on the necessity of minds to interact with the world, for which a body is necessary (Dancy and Ritter, 2017, p. 316). Furthermore, the body plays an essential role in maintaining the necessary conditions for a organism to operate in, including supplying the brain with resources (ibid.). I believe it is important to reflect on the fact that ACT-R was not developed with a body in mind. Perception and motor modules that would allow modelers to create “embodied” ACT-R models were not added until around 2007 (Anderson, 2007, Figure 1.11 on p. 39).

Now that I laid out the assumptions inherent in choosing ACT-R, primary affect, and HumMod, I will discuss the theoretical basis for implementing an interface between the three theories: “subsymbolic” processing.

2.2 The Interface between ACT-R, Primary Affect, and HumMod: “Subsymbolic” Processing

ACT-R is a hybrid cognitive architecture that integrates symbolic and “subsymbolic” elements (Anderson, 2007, p. 33). It is the “subsymbolic” elements that are targeted by ACT-R/Phi and I believe it is important to discuss what “subsymbolic” means in the context of ACT-R.

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[5] Common Model of Cognition.

It is important to point out that “subsymbolic” processing in ACT-R has nothing to do with neural networks. ACT-R does not contain neural networks that carry out computations. *“subsymbolic”* is “*[...] an abstract characterization of the role of neural computation in making that knowledge available.*” (Anderson, 2007, p. 33). Anderson concedes that Christian Lebiere and he did not think too deeply about the implications of calling this abstract characterization “subsymbolic” (Anderson, 2007, p. 33, footnote 28). What ACT-R does contain is metadata, or “*just numeric processing for conflict resolution and things like that*” (Nagashima et al., 2022, m. 19:50). This metadata operates in the background. It is invisible to ACT-R models but still influences memory retrieval processes and model performance. It is precisely the metadata which is modulated by ACT-R/Phi based on values from the HumMod physiology system (Dancy, 2014, p. 69).

Nevertheless, ACT-R does contain metadata/numerical processing that is not accessible to the simulated Agents in ACT-R models. For example, ACT-R contains global parameters such as the :ans (activation noise s) parameter[6]. These global parameters influence ACT-R model behavior in the background: without explicit interaction from/with the model. The activation noise s (:ans) parameter for example, adds *noise* to the activation, equation which determines which chunk will be retrieved from declarative memory next. *Noise* is present in ACT-R to influence which items in memory are selected next. Generally, the item with the highest value is selected but the noise component adds variability. While this can produce errors and suboptimal behavior, it also allows for the exploration of new/different strategies that could be beneficial to solving a task (Taatgen et al., 2006, p. 32).

Based on my current understanding physiology from HumMod modulates two global ACT-R parameters: activation noise s (:ans), and expected gain s (:egs)[7].

When thinking of the way how ACT-R/Phi modulates “subsymbolic” properties in ACT-R I believe it is important to reflect on the role of these “subsymbolic” properties in ACT-R. Anderson (2002) discusses the difficulties that arise once going down to the “subsymbolic” level (p. 109). He states, that *“in many applications it is not necessary to know exactly what a person is doing at a fine-grained level”* (ibid.). However, Anderson does suggest that information at the “subysmbolic” level could be interesting when it

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[6] “Recommended values for the noise parameter are in the range [.2,.8].”(Bothell, 2023, p. 299)

[7] When the utility module is activated (it is not by default), productions in ACT-R will be associated with a numeric (“subsymbolic”) utility value. The :egs parameter adds noise to this utility value.

comes to decomposing bigger unit-tasks (which are often modeled in ACT-R) into their components (ibid.). Whether modeling unit-tasks at a sub-unit-task level makes sense, depends on our assumptions about the role of the internal structure in relation to the phenomenon we are interested in. As Simon (1996) points out, it is easier to simulate a phenomenon as abstraction increases (p. 16) and it is the task of the modeler to find a sufficient abstraction. I will discuss further thoughts related to this question in Section 6.2.

2.3 The ACT-R/Phi Modules

ACT-R/Phi consists of four modules which can be further divided into the Physiological System or the Affective System. An overview of the structure is given in Figure 2.1.

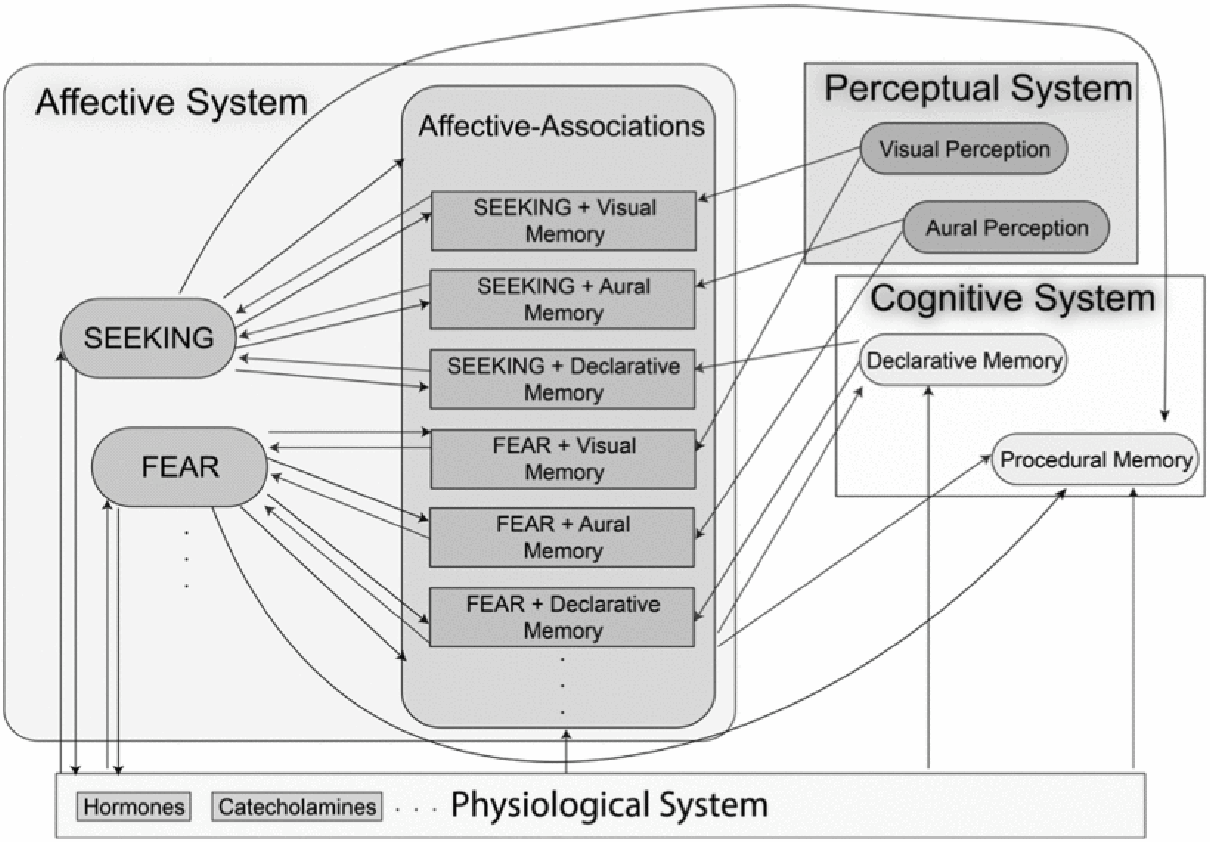

Figure 2.1: Illustration of the ACT-R/Phi modules: SEEKING, FEAR, Affective Associations and the Physiological System consisting of the Physiology module and HumMod © 2021 IEEE. Reprinted, with permission, from Dancy (2021)

- Physiology module

- Affective Associations Module
- FEAR Module
- SEEKING Module

I will describe the theoretical function of these modules here, before I will discuss the implementation of ACT-R/Phi in Chapter 3.

2.3.1 Physiology Module

The Physiology module implements the interface between HumMod and ACT-R. The Physiology module contains the functions to start the HumMod physiology simulation as well as the functions that send commands to HumMod and receives the output (physiology values) from HumMod.

2.3.2 Affective Associations Module

The Affective Associations module implements the functions that calculate ACT-R parameter values based on physiological values retrieved from HumMod. Functions in the module implement that *noise* is added when calculating activation values for chunks based on the state of the HumMod simulation. Thus, depending on the physiological state of HumMod, ACT-R chunks are processed with corresponding memory noise: Thus, chunks processed at time x, carry some representation of the physiological state. Additionally, the Affective Associations module serves as the interface between the SEEKING and FEAR modules and the ACT-R procedural and declarative memory modules (Dancy, 2014, p. 79). The Affective Associations influences the retrieval of elements in declarative memory by modulating the “subysmbolic” properties of these elements based on the current affective state (Dancy, 2021, p. 324f). This way, elements that were present during e.g. a high FEAR state, are more likely to be recalled when there is another high FEAR state.

2.3.3 FEAR Module

The FEAR module implements the reaction to unconditioned (negative) stimuli based on the FEAR system proposed (Panksepp and Biven, 2012, p. 116).

The FEAR module checks the Affective Associations module in ACT-R for FEAR related stimuli. If a FEAR related stimulus is present, it will influence ACT-R memory structures (Dancy, 2014, p. 75f). The module checks the location buffers outside of normal ACT-R processing cycles (ibid., p. 103). This means that information like the affective value of an object in the location buffers will only be processed by the ACT-R/Phi modules.

For the Affective Associations module to pick up FEAR related affective stimuli, requires these stimuli (e.g. pictures) need to be prepared to include an affective value. The affective value of a stimulus needs to be hard-coded based on e.g. human ratings and are not evaluated inside the ACT-R/Phi modules.

2.3.4 SEEKING Module

The SEEKING module implements a general brain reward system of motivation based on the SEEKING system proposed by Panksepp and Biven (2012, p. 73). As implemented, the SEEKING module is informed by a physiological measure of thirst in HumMod (Dancy, 2014, p. 71f). If the SEEKING value detects a high value of thirst it should "motivate" the agent to change goals more readily in order to find a "solution" to this homeostatic imbalance (Dancy, 2021, p. 323). Increase in physiological thirst will also affect procedural and declarative memory through the Affective Associations module (Dancy, 2014, p. 71f).

2.3.5 Summary

The four ACT-R/Phi modules serve distinct purposes. The Physiology module implements the interface between ACT-R and HumMod. The Affective Associations module implements the functions that influence declarative and procedural memory by adding *noise* based on physiological values and implements the influence of the SEEKING and FEAR modules on procedural memory. The FEAR module implements functionality to influence prodedural and declarative memory "subsymbolically" based on the presence of affective stimuli such as a picture of a spider. The SEEKING module implements funtionality to influence prodedural and declarative memory "subsymbolically" based on the presence of homeostatic imbalance such as thirst.

2.4 Example ACT-R/Phi Models

In order to provide a picture of what ACT-R/Phi has been used for I will provide an overview of four models that use the ACT-R/Phi modules in varying capacity.

2.4.1 Iowa Gambling Task Model

ACT-R/Phi has been used to model a version of the Iowa Gambling Task (IGT) that includes affective stimuli in the form of pictures of, for example, snakes or spiders (Dancy, 2014, p. 96). In the IGT participants must select cards from four decks. Two of the decks are "good" decks which yield a positive outcome on average and two of the decks are "bad" decks which lead to a negative outcome on average. In the ACT-R/Phi IGT model, affective stimuli were presented for 17ms after the model selected a "bad" deck (ibid., p. 99). This way the "bad" decks became associated with a higher FEAR value which caused the model to choose these decks less frequently. The affective value of the pictures presented was coded into the picture based on human ratings and not evaluated by the cognitive architecture. The purpose of the ACT-R/Phi IGT model is to showcase the functioning of the FEAR and Affective Association modules as well as – to a lesser extent, since the focus is on affective stimuli that activate the FEAR module – the SEEKING module (ibid., p. 103). The IGT model does not make use of the Physiology system.

2.4.2 Stress Model

ACT-R/Phi has been used to model the effect of stress on a mental subtraction task. A loud noise was simulated ans used as a trigger to simulate stress in HumMod by activating the "CNS integration nerve" which causes epinephrine levels to raise (Dancy, 2014, p. 86). The raising epinephrine levels then affects the declarative memory *noise* which interferes with the models ability to retrieve the correct chunks from memory (ibid.). The purpose of the ACT-R/Phi stress model is to showcase the functioning of the Physiology system (HumMod + Physiology module).

2.4.3 Thirsty Model

ACT-R/Phi has been used to model the effect of homeostatic imbalance (physiological thirst) on decision making in a modified version of the Ultimatum Game (Dancy, 2014,

p. 90). In the modified version of the Ultimatum Game, proposers offered the participants water (the proposer was allowed to "split" a glass of water between them and the participant) instead of money (ibid.). The participant is allowed to accept or reject an offer. In the thirsty model the physiology simulation was used to administer a hypertonic saline infusion to induce physiological thirst (ibid.). The infusion changed the osmolarity of the HumMod simulation which resulted in the model being "thirsty". Because it was "thirsty" the model selected offers that would allow it to "drink", even if the offer by the proposer was not favorable (ibid., p. 91ff). The purpose of the ACT-R/Phi Thirsty model is to showcase the functioning of the Physiology system and the SEEKING module.

2.4.4 Slow Breathing Model

ACT-R/Phi has also been used to model the effects of simulated slow breathing on performance on a mental subtraction task (Dancy and Kim, 2018). The model builds on the Stress model mentioned above and adds a simulated one minute deep breathing session which should reduce stress (ibid., p. 1593). The purpose of the ACT-R/Phi Slow Breathing model is to showcase the functioning of the Physiology system while intervening with multiple HumMod variables.

2.4.5 Summary

ACT-R/Phi has been used to implement at least four models that make use of the ACT-R/Phi modules in varying capacity. While the Thirsty, Stress, and Slow Breathing models utilize the Physiology system, the IGT model focuses on processing affective picture stimuli and associating them with other elements in memory based on the Affective Associations and FEAR modules. The models implemented in ACT-R/Phi demonstrate the functionality of the various modules making up ACT-R/Phi – with and without the Physiology system – and provide inspiration for interventions that could be implemented.

2.5 Summary of the Chapter

ACT-R/Phi is a theory and its computer implementation. The theory formulates how the cognitive architecture ACT-R can be enriched with physiological data from the HumMod simulation. This is achieved by taking a *circuit theory* of emotion that links physiological processes with certain brain functions. Research in ACT-R focuses on reproducing human-like performance on a series of tasks by creating appropriate models of human-like behavior. Researchers have localized activity in brain areas of human subjects that correspond to the activity in ACT-R modules while both were performing the same task. Based on these results, ACT-R modules have been grounded in certain brain areas. Knowledge about the neurophysiology of these brain areas allows relating these brain areas to physiological variables. These physiological variables are then used to modulate the functioning of ACT-R parameters, grounding ACT-R/Phi activity in simulated physiology.

Chapter 3

ACT-R/Phi: Practical

the purpose of this chapter is to introduce the cognitive architecture ACT-R/Phi from a user's perspective. Discussing the practical implementation of ACT-R/Phi in more detail will allow me to relate the theoretical considerations to the practical implementation. ACT-R/Phi extends ACT-R with a physiological system consisting of the HumMod physiology simulation and the Physiology module, as well as a SEEKING module, a FEAR module and Affective Associations module (Dancy, 2021, p. 323ff). Given my interest in the mind-body interfaces between ACT-R and HumMod, my primary focus during my exploration of ACT-R/Phi was on the physiology system consisting of HumMod and the Physiology module. Nevertheless, I will discuss the additional modules besides the physiology system.

Furthermore, I will describe the flow of information through ACT-R/Phi, ignoring the division of program code across the ACT-R/Phi modules. This allows me to illustrate how information from HumMod modulates ACT-R/Phi parameters and how information from ACT-R/Phi modulates HumMod parameters.

To illustrate the practical usability, I will also describe how I modified a ACT-R model to utilize the ACT-R/Phi physiology system. This is a mere exercise to showcase the relative ease with which an ACT-R model can be modulated using the physiology system from ACT-R/Phi.

ACT-R/Phi is available at `https://git.psu.edu/thicc-lab/act-r_phi` (accessed 2024-09-12) and a manual on how to get ACT-R/Phi up and running is included in Appendix A.

3.1 ACT-R/Phi the Artifact

ACT-R/Phi makes use of the modular nature of ACT-R. All the files that are required to run ACT-R/Phi are present in the `act-r_phi-main‣user-loads` folder. ACT-R attempts to load everything in this folder when starting up[1].

3.1.1 The Physiology System

The physiology system consists of a customized version of HumMod as well as the ACT-R/Phi Physiology module.

HumMod

HumMod is *"The most complete, mathematical model of human physiology ever created"* (HC Simulation, LLC, 2016). HumMod serves as the physiology substrate for ACT-R/Phi. HumMod model details are stored in XML files in the `act-r_phi-main‣user-loads‣Data` folder. This makes the details more accessible and humanly readable (Hester et al., 2011, p. 1). Using the user interface[2], the HumMod simulation can be advanced by seconds up to days, weeks and months. In ACT-R/Phi, HumMod is advanced by writing commands into a text file that HumMod is constantly listening for.

In addition to work on the ACT-R/Phi modules, Dancy also modified HumMod by creating and modifying some of the HumMod XML files. For example, the ControlledBreathing.DES file implements functionality that allows the modeling of the breathing rate and volume. The total list of modified HumMod files is: ACTH.DES, Breathing.DES, ControlledBreathing.DES, CorticotropinReleasingFactor.DES, Cortisol.DES, DailyPlannerControl.DES, Lungs.DES, Status.DES, Sympathetics-Cardiac.DES.

The HumMod version used by ACT-R/Phi is thus distinct and can not be exchanged by a different HumMod version.

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[1] ACT-R also comes with optional modules that are shipped with the main software. These optional modules are located in the *extras* folder. ACT-R/Phi is not such a module.

[2] While HumMod has a graphical user interface (GUI) that loads when executing the HumMod.exe, the version that is shipped with ACT-R/Phi crashes when trying to load – probably because of modified HumMod files. For this reason it can be instructive to acquire a HumMod version that has a functioning GUI if one is interested in exploring the capabilities of HumMod. Standalone versions of HumMod can be downloaded from the HumMod website: `https://hummod.org/agreement` (accessed 2024-09-16). Project specific versions are available: `https://hummod.org/projects/` (accessed 2024-09-16).

Physiology Module

The ACT-R/Phi Physiology module (Physiology_thread-lisp) serves as the interface between HumMod and ACT-R and was of particular interest to my investigation. Functions in the Physiology module are responsible for starting the HumMod simulation and for keeping HumMod and ACT-R/Phi synchronized. The Physiology module also contains the functions that send commands to HumMod and read output from HumMod. I describe the functioning of the Physiology system in detail in Section 3.2.

3.1.2 Affective Associations Module

The Affective Associations module serves multiple purposes. It checks the ACT-R buffers for the presence of affective stimuli for the FEAR module. The Affective Associations module also attaches affective values from the SEEKING and FEAR modules to chunks of the Visual, Aural and Declarative modules in order to encode the current affective state in elements that are also present at that time. This leads to a higher likelihood of the system to retrieve chunks that have a similar affective value attached as the current affective state (Dancy, 2021, p. 324f).

The Affective Associations module implements two *:activation-offsets* – one for FEAR and one for SEEKING. The *:activation-offsets* ACT-R parameter extends the activation equation by based on the values of the FEAR and SEEKING modules.

3.1.3 SEEKING Module

The SEEKING module utilizes the global ACT-R parameter *:utility-offsets* (Bothell, 2023, p. 261) to extend the utility equation based on the calculated SEEKING value. By influencing the utility equation the retrieval of elements in procedural memory (productions) is influenced based on the current SEEKING state. The SEEKING state is computed as a competition between measures of *thirst*, *hunger*, or *skin temperature*. *Thirst* is calculated based on the physiological variable $OsmBody.CellWall(mOsm/L)$ (see Figure 3.2). In addition to modulating the utility calculation, the SEEKING module adds a separate SEEKING parameter to productions based on the current SEEKING value.

3.1.4 FEAR Module

The FEAR module calculates a FEAR value based on the presence of affective stimuli in the Visual, Aural, and Declarative modules as well as based on the presence of e.g. painful stimuli based on the Physiology module[3]. The FEAR module also utilizes the global ACT-R parameter *:utility-offsets* (Bothell, 2023, p. 261) to extend the utility equation based on the calculated FEAR value. In addition to modulating the utility calculation, the FEAR module adds a separate FEAR parameter to productions based on the current FEAR value.

The FEAR module also implements a direct connection to physiology and modulates HumMod by setting the *SympsCNS.ClampSwitch* and *SympsCNS.ClampLevel* variables based on the current FEAR value (see Figure 3.2).

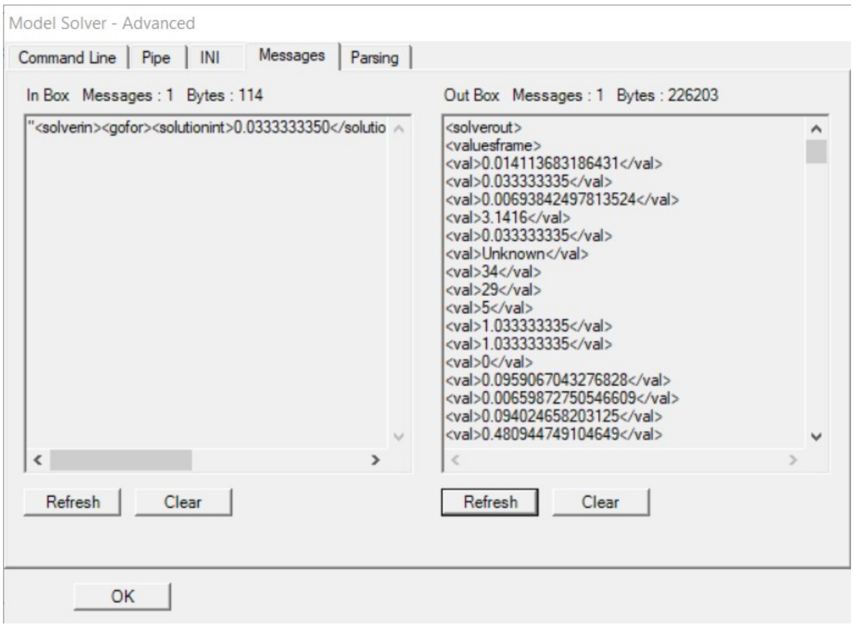
3.2 The Interface

The implementation of ACT-R/Phi hinges on the interaction between ACT-R and HumMod through the additional ACT-R/Phi modules. Since HumMod and ACT-R are two separate software, it is important to look in detail how communication between them is implemented. The implementation of this interface dictates to what extent HumMod and ACT-R/Phi interact.

The interface between ACT-R and HumMod is realized in the Physiology module (Physiology_thread.lisp). The Physiology module contains functions that facilitate the exchange of data with HumMod. The communication between ACT-R and HumMod is realized in the form of exchanging two text files. The *SolverIn.txt* file contains instructions to HumMod and the *SolverOut.txt* file contains information from HumMod. Typical instructions in the *SolverIn.txt* file include setting the value of a HumMod variable and advancing the physiology simulation. Typical content in the *SolverIn.txt* file are lists of variables and lists of variable values.

---

[3] Based on my understanding of the program code, this functionality is not connected to a variable from HumMod



In Box Messages : 1 Bytes : 114

```
"<solverin><gofor><solutionint>0.0333333350</solutio
```

Out Box Messages : 1 Bytes : 226203

```
<solverout>
<valuesframe>
<val>0.014113683186431</val>
<val>0.033333335</val>
<val>0.0069384249781 3524</val>
<val>3.1416</val>
<val>0.033333335</val>
<val>Unknown</val>
<val>34</val>
<val>29</val>
<val>5</val>
<val>1.033333335</val>
<val>1.033333335</val>
<val>0</val>
<val>0.0959067043276828</val>
<val>0.00659872750546609</val>
<val>0.094024658203125</val>
<val>0.480944749104649</val>
```

Figure 3.1: Screenshot of the HumMod Model Solver. The In Box (SolverIn) on the left contains instructions to advance the HumMod simulation by two seconds (0,0333333350 minutes). The Out Box (SolverOut) on the right contains a list with the current values of the HumMod simulation.

3.2.1 Communication/Synchronization

Every time when an ACT-R/Phi model runs the HumMod ModelSolver is launched. Before the ModelSolver is launched, ACT-R/Phi calculates a *PipeID*. HumMod is launched with this *PipeID* which serves as the identifier for the ACT-R/Phi instance and HumMod instance[4]. This PipeID is added to the *SolverIn* and *SolverOut* filenames by the ACT-R/Phi modules and determines which files HumMod is looking for and will produce.

3.2.2 SolverIn: Sending Commands to HumMod

Whenever a file with the appropriate PipeID called *SolverIn* is created, the HumMod Model Solver reads the contents of this XML file and executes what is requested. The possible actions are: 1) Advancing the physiology simulation by a set amount of time 2) setting the value of a HumMod variable 3) restarting the HumMod simulation 4) loading a set of initial conditions (.ICS files) which set the HumMod simulation into a certain state.

---

[4] Theoretically, multiple ACT-R/Phi instances could be operated simultaneously.

Once the ModelSolver processed a SolverIn file, it will produce a SolverOut file that will also include the appropriate PipeID. The content of the SolverOut file is read by a function in the ACT-R/Phi Physiology module. Generally, the SolverOut file contains a list of values that represent the current simulated physiological state in HumMod.

SolverIn and SolverOut files are periodically deleted by functions in the ACT-R/Phi Physiology module. This is necessary because there is no direct communication channel between HumMod and ACT-R/Phi which could be used to confirm that a command was executed. ACT-R/Phi relies on waiting for an appropriate time for the HumMod Model Solver to process the requested commands from the SolverIn file before deleting the file. SolverOut files are deleted after they have been processed by ACT-R/Phi.

The HumMod model solver essentially operates on its own and waits for input in form of SolverIn files to which it responds by outputting SolverOut files.

Setting a Value (or looping through many values)

Listing 3.1: Command to set a HumMod variable (ControlledBreathing.RespRate) to a value (20).

```
<solverin><setvalue><var>ControlledBreathing.RespRate 20</var></setvalue></solverin>
```

Advancing the Simulation (in Minutes)

Listing 3.2: Command to advance the HumMod simulation by 0 0333333350 minutes (2 seconds).

```
<solverin><gofor><solutionint>0.0333333350</solutionint><displayint> X </displayint></gofor></solverin>
```

Listing 3.3: Command to restart the HumMod simulation

```
<solverin><restart/></solverin>
```

3.2.3 SolverOut: Receiving Data from HumMod

SolverOut files contain output messages from the HumMod Model Solver. Usually, this is a list of physiology values representing the current state of the HumMod Physiology simulation. Initially the *SolverOut* file contains a list of all variable names that are present in HumMod. Subsequently the *SolverOut* file contains a list of values where the position of each value corresponds to the position of the variable name in the initial list. A *SolverOut* file is produced by HumMod after every time the physiology simulation was advanced.

The content of these lists are stored in ACT-R/Phi and thus, the current values of all physiological variables can be processed in ACT-R/Phi.

3.3 Influence of HumMod Variables on ACT-R Parameters

Now that we understand how the state of HumMod is passed along to ACT-R/Phi, the question is how the values of certain physiological variables influence the performance of the cognitive architecture.

To understand this, we need to turn to two important parameters within ACT-R in general: the ans (activation noise s) and egs (expected gain s) parameters. These parameters are central to the functioning of ACT-R. Changing the :ans and :egs values dynamically, based on the state of the HumMod simulation, is the primary way in which the performance of ACT-R/Phi is connected to HumMod.

3.3.1 The activation noise s parameter :ans

The :ans parameter stands for activation noise s. S is a parameter that is added to the activation equation. By default :ans is set to nil that means that no additional noise is added to the activation equation (Bothell, 2023, p. 299). In ACT-R/Phi the :ans value is modified based on arousal level using the :noise-hook function.

3.3.2 The expected gain s parameter :egs

The :egs parameter stands for expected gain s. S is a parameter for the noise added to calculations of utility values (Bothell, 2023, p. 259). By default, ACT-R does not use noise in utility calculations. In ACT-R/Phi the :egs value is modified based on arousal level using the :utility-hook function.

3.3.3 :noise-hook and :utility-hook

ACT-R modelers can specify so called hook functions. The purpose of these functions is to override default parameter calculations in ACT-R. If a hook function is set, it will be called whenever a parameter value needs to be calculated. ACT-R/Phi uses the *:noise-hook* and the *:utility-hook* functions.

The *:noise-hook* function overrides the default noise calculation in ACT-R. Every time a noise value is needed for a chunk in order to determine which chunk will be retrieved from memory, the noise value is calculated using the function specified in the *:noise-hook*. If the function returns a number that number will be used in the activation equation for that particular chunk.

In ACT-R/Phi, the *:noise-hook* is set to the $dm - noise - aa$ function (Listing 3.4). Every time ACT-R needs to calculate an activation value, it will invoke the $dm-noise-aa$ function and the result of the calculation – based on physiology – will influence which chunk is retrieved from memory.

Listing 3.4: the dm-noise-aa function is called using the :noise-hook every time a activation noise value needs to be calculated for a chunk. dm-noise-aa calculates the :ans value is calculated.

```
(defun dm-noise-aa (chunk)
    (declare (ignore chunk))
    (let* ((aa (get-module Affective-Associations))
            (arous-dm-noise (compute-arousal-factor (
               AA-pred-error-factor aa)))
            (arous-mid (/ (AA-max-arous aa) 2))
            (noise-val 0))
         (when (= arous-dm-noise 0) (incf arous-dm-noise 0.000001))
         (if (<= arous-dm-noise arous-mid)
            (setf noise-val (/ (+ (* arous-dm-noise (AA-nom-dm-noise aa)
               ) (* (- arous-mid arous-dm-noise) (AA-max-dm-noise aa)))
               arous-mid))
            (setf noise-val (/ (+ (* (- (AA-max-arous aa) arous-dm-noise
               ) (AA-nom-dm-noise aa)) (* (- arous-dm-noise arous-mid) (
               AA-max-dm-noise aa))) arous-mid)))
         (no-output (sgp-fct (list :ans noise-val)))
         (setf noise-val (act-r-noise noise-val))
         noise-val))
```

The *:utility-hook* parameter overrides the default utility calculation with . It can be set to a command identifier for a command which must take one parameter. If the *:utility-hook* parameter is not nil (which is the default value) then each time the utility value of a production is calculated, first this hook command is called with the name of the production as the parameter. If that command returns a number then that number is used as the production's utility instead of using the normal mechanisms. In ACT-R/Phi the *:utility-hook* is set to the $util - noise - aa$ function (Listing 3.5).

Listing 3.5: the util-noise-aa function is called using the :utility-hook and calculates the utility noise value egs.

```
(defun util-noise-aa (production)
        (let* ((aa (get-module Affective-Associations))
                egs
                ut
                prod-utility
                arous-util-noise
                addNoise
                (arous-mid (/ (AA-max-arous aa) 2)))
        ;;Get normal utility of production
        (sgp-fct (list :utility-hook nil :egs 0))
        (setf prod-utility (compute-utility production))
        (sgp-fct (list :utility-hook 'util-noise-aa))
        (setf arous-util-noise (compute-arousal-factor (
            AA-pred-error-factor aa)))
        #|(with-open-file
                (messageStream "arousalLevels.txt" :direction :output :
                    if-exists :append :if-does-not-exist :create)
                (format messageStream "~a~&" arous-util-noise))|#
        (when (<= arous-util-noise 0) (setf arous-util-noise 0.000001))
        (if (<= arous-util-noise arous-mid)
                (sgp-fct (list :ut (* (AA-util-thresh-scalar aa) (- (
                    AA-max-util-thresh aa) arous-util-noise));(- (
                    AA-max-util-thresh aa) (* (- 1 (/ arous-util-noise
                    0.5)) (AA-max-util-thresh aa) ))))
                        :egs (* (AA-util-noise-scalar aa) (/ (+ (*
                            arous-util-noise (AA-nom-util-noise aa)) (*
                            (- arous-mid arous-util-noise) (
                            AA-max-util-noise aa))) arous-mid))))
```

```
            (sgp-fct (list :ut (* (AA-util-thresh-scalar aa) (- (
               AA-max-util-thresh aa) arous-mid))
                   :egs (* (AA-util-noise-scalar aa) (/ (+ (* (- (
                      AA-max-arous aa) arous-util-noise) (
                      AA-nom-util-noise aa)) (* (- arous-util-noise
                       arous-mid) (AA-max-util-noise aa)))
                      arous-mid)))))
```

3.4 Information Flow

In order to understand how physiological values from HumMod are processed by ACT-R/Phi and to understand how ACT-R/Phi modulates HumMod I investigated how information related to HumMod is processed in the ACT-R/Phi modules. For this purpose I followed two paths that I will present here. Firstly, I investigated the physiology variables from HumMod that could be set from within ACT-R/Phi. Secondly, I investigated the physiology variables that are read by by ACT-R/Phi modules.

3.4.1 HumMod values used by ACT-R/Phi

To understand how physiology values from HumMod are processed by ACT-R/Phi I investigated functions in the ACT-R/Phi program code that required input in the form of physiology values. Whenever a function in ACT-R/Phi requires the current (or baseline) value of a HumMod variable it uses the $get-phys-vals$ function which requires the full name of a HumMod variable and looks up the corresponding value of this variable in a list of lists.

Based on the $get-phys-vals$ function I identified all functions within the ACT-R/Phi code that directly request the value of a physiology variable. All of these functions are represented in Figure 3.2.

There are nine distinct variables from HumMod that are read by ACT-R/Phi modules. These nine variable belong to five categories as listed below:

- CRH Arousal
    - CorticotropinReleasingFactor.[CRF(pG/mL)]
    - CorticotropinReleasingFactor.StressEffect

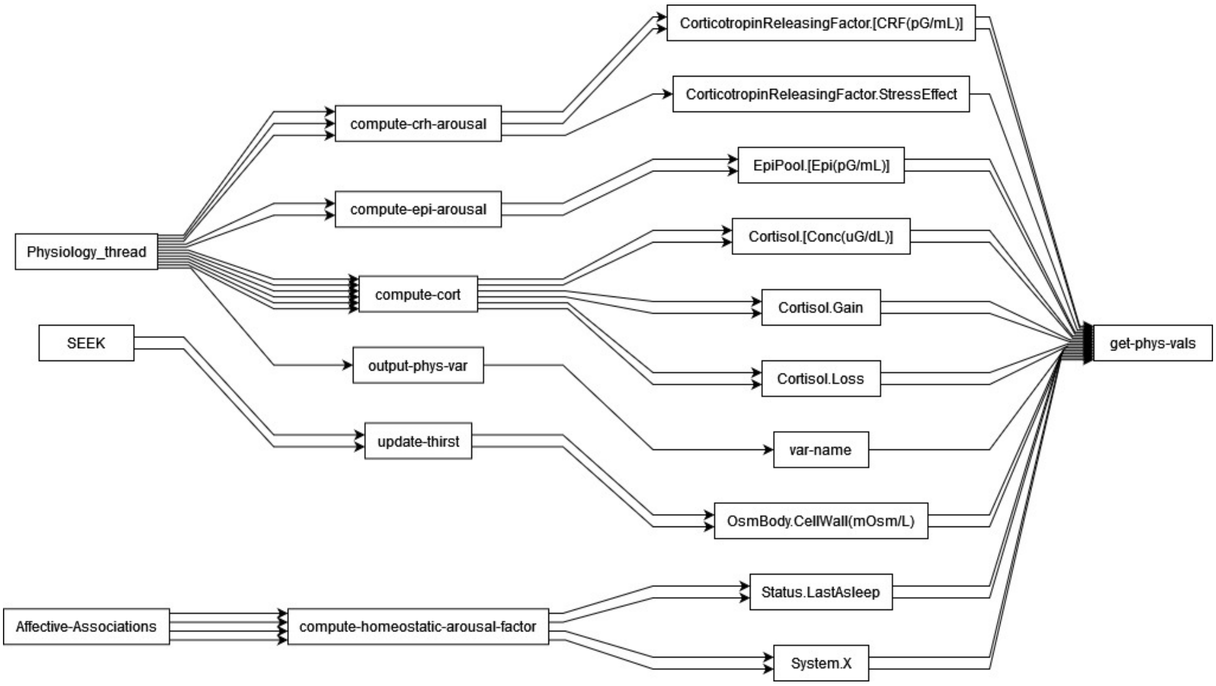


Figure 3.2: Overview of physiology variables that are read by ACT-R/Phi Modules. Multiple arrows to a single variable indicate that the current and a second value (e.g. baseline) of the same variable is read. Levels of the chart from left to right: 1. ACT-R/Phi module, 2. function within module, 3. physiological variable, 4. get-phys-vals function (reads physiology values from list).

- Cortisol
  - Cortisol.[Conc(uG/dL)]
  - Cortisol.Gain
  - Cortisol.Loss
- Epinephrine
  - EpiPool.[Epi(pG/mL)]
- Homeostatic Arousal Factor
  - Status.LastAsleep (time)
  - System.X (time?)
- Thirst
  - OsmBody.CellWall(mOsm/L) (Thirst)

Out of the HumMod variables mentioned above, all - save for OsmBody are all called by the $compute-arousal-factor$ function which is in turn called by the $dm-noise-aa$

function. The $dm - noise - aa$ function is of particular interest, since it is the function that is called every time when ACT-R needs to calculate the noise value of a given chunk. The compute-arousal function returns a single value based on internal calculations and is subsequently used by the $dm - noise - aa$ function that is invoked by a hook function that I will introduce in the next section.

In addition to the values listed, the $output - phys - var$ function takes a variable name as input and returns the value of the requested variable.

3.4.2 HumMod values modified by ACT-R/Phi

In order to understand how HumMod values are modified by ACT-R/Phi I proceeded in the same fashion as above, but this time following the $set - phys - vals$ function. The $set - phys - vals$ function is used to set HumMod variables to certain values. This is achieved by writing a SolverIn text file containing the instructions which variable should be set to which value. The $set - phys - vals$ function is primarily used by the Physiology module by functions such as the $start - slow - breathing$ or the $create - high - stress$ functions. In addition to these predefined functions, the $set - phys - vals$ function can be called individually to set a HumMod variable to a desired value. This requires knowledge of the exact HumMod variable name targeted and knowledge about appropriate values for this variable. The manual for HumMod compiled by Brener et al. (2019) is probably the best resource for the purpose of acquiring this knowledge and better understanding HumMod in general.

3.4.3 Summary

In ACT-R/Phi the :noise-hook and :utility-hook values are set. The hooks invoke functions that in turn depend on the current state of HumMod simulation. This changes the way in which noise and utility are calculated which are central to the general functioning of ACT-R.

3.5 Running a Model in ACT-R/Phi

In order to verify my knowledge of ACT-R/Phi and trial the implementation I decided to modify an ACT-R model to run utilizing the ACT-R/Phi physiology system. For this

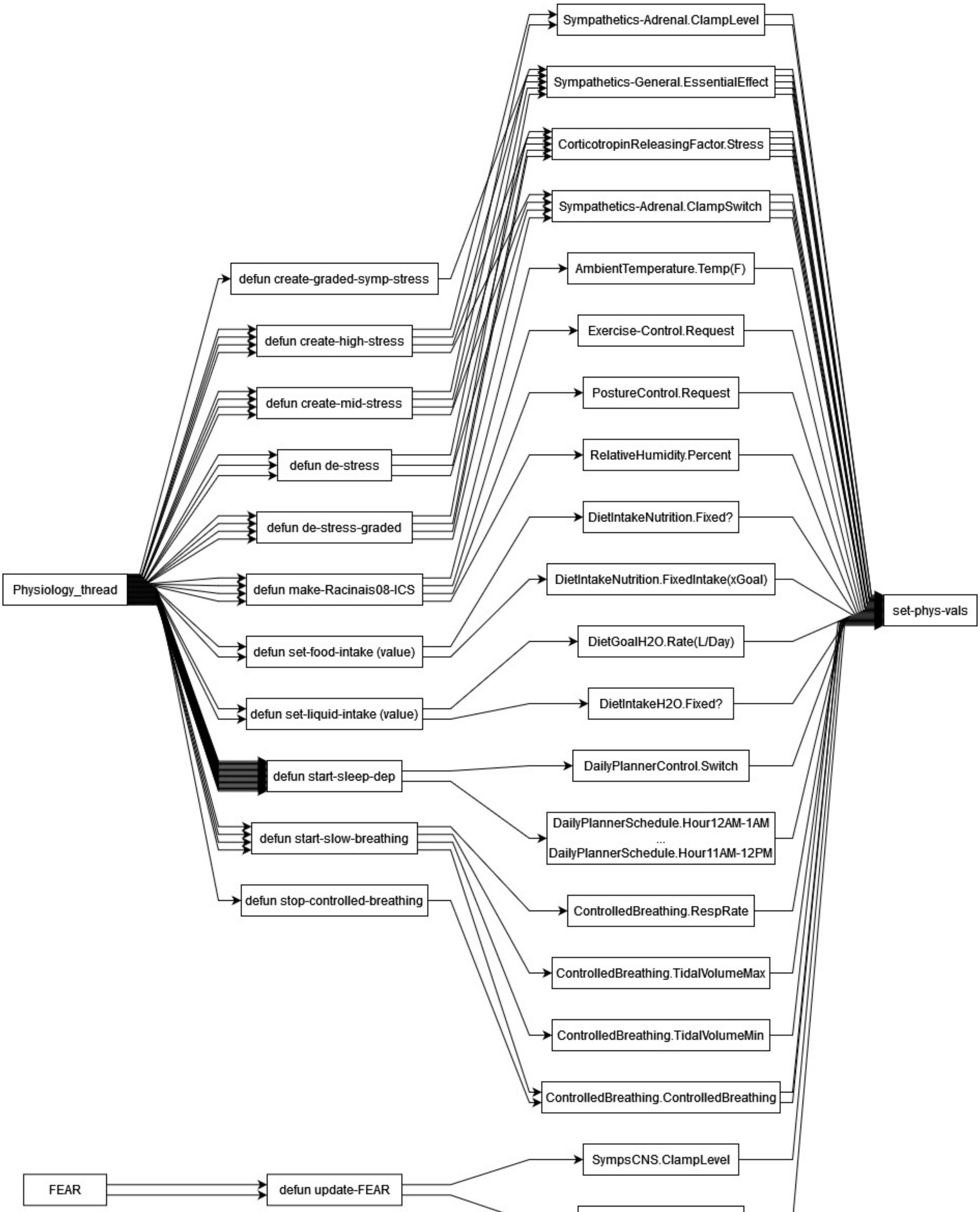


Figure 3.3: Overview of all the physiology variables that are set by ACT-R/Phi Modules. Levels of the chart from left to right: 1. ACT-R/Phi module, 2. function within module, 3. physiological variable, 4. set-phys-vals function (writes file to be read by HumMod).

purpose I selected the *zbrodoff-model*, which is part of the ACT-R tutorial.

The Zbrodoff task is a alphabet arithmetic task where subjects are presented with equation like A + 2 = C. Subjects need to evaluate whether the equation is true or false and respond accordingly. In this case, the equation is true since moving two letters forward from A results in C.

3.5.1 Necessary Modifications

In order to enable the ACT-R/Phi modules in the zbrodoff-model, I copied settings from the ACT-R/PhiTest-Model.lisp located in the `act-r_phi-main▸phys-test-models` folder. The sgp function in ACT-R is used to set module parameters. The *phys-enabled* parameter enables the Physiology module. Enabling the Physiology module will in turn invoke the start of HumMod.

Listing 3.6: Parameters used to invoke ACT-R/Phi modules

```
(sgp :v nil :esc t :lf 0.4 :bll 0.5 :ans 0.5 :rt 0 :ncnar nil)
(sgp :esc t :lf .05 :trace-detail high)
(sgp :phys-delay 2 :phys-enabled t)
(sgp :AA-enabled t)
(sgp :AA-dm-noise-switch t)
(sgp :AA-util-noise-switch nil)
(sgp :AA-max-dm-noise 1)
(sgp :ut -999 :ans .5)
```

3.5.2 Potential Modulations

Once the ACT-R/Phi modules are enabled, we can utilize the functions of the modules to interact with HumMod. For example, we can modulate the breathing rate by setting the appropriate variable to a desired value.

Listing 3.7: ACT-R command to schedule the modulation of the breathing rate in HumMod

```
(schedule-event 0.022 'set-phys-vals :module 'physio :params
    (list (list (list "ControlledBreathing.RespRate" 20)
    (list "ControlledBreathing.TidalVolumeMax" 3000)
    (list "ControlledBreathing.TidalVolumeMin" 1200)
    (list "ControlledBreathing.ControlledBreathing" 1)))
```

```
    :priority :max :details "Start Controlled Breathing")
```

Listing 3.8: ACT-R trace of the breathing rate being modulated to 20 breaths per minute

```
0.022   PHYSIO  Start Controlled Breathing
Changing the following physiology:
((ControlledBreathing.RespRate 20)
    (ControlledBreathing.TidalVolumeMax 3000)
    (ControlledBreathing.TidalVolumeMin 1200)
    (ControlledBreathing.ControlledBreathing 1))
```

Besides setting HumMod variables to certain values there are functions in place that allow us to record the values of physiology variables as well as ACT-R system parameters (:ans, for example) over time.

Listing 3.9: Recording physiological values in ACT-R/Phi using the test-record-arousal function that includes ACT-R system parameters as well as HumMod variable values

```
(schedule-periodic-event 1 'test-record-arousal :module :physio :output
   nil :initial-delay 2)
```

time.s	Homeostatic-Arousal-Factor	f(Cortisol)	g(Epinephrine)	h(CRH)	Arousal	ans
3.00	1.00000	0.99892	0.99985	0.99491	0.99631	0.43638
4.00	1.00000	0.99785	0.99970	1.00615	1.00077	0.43638
795.00	0.99996	0.74327	0.97767	1.13216	0.78406	0.55645
796.00	0.99996	0.74289	0.97774	1.12624	0.78149	0.55645
1594.00	0.99986	0.63661	1.01960	1.11828	0.68041	0.61366
1595.00	0.99986	0.63661	1.01960	1.11828	0.68041	0.61366

Table 3.1: Example of recorded ACT-R parameter and HumMod variable values

3.5.3 Comparing Model Parameters

Firstly, it is important to emphasize that when running an ACT-R model in ACT-R/Phi there is no change in runtime or experimental results. Given general compatibility every

ACT-R model can be executed in ACT-R/Phi without modifications and without changes in results.

Figure 3.4 shows the change of the :ans parameter over time in three different conditions: without intervention, with breathing rate set to four breaths per minute, and with the breathing rate set to twenty breaths per minute.

The :ans parameter stabilizes after about 26 simulated minutes in all conditions which coincides with the end of the experiment. The parameter settles at different values for each of the three conditions: $0,61401$ for twenty breaths, $0,59782$ for four breaths, and $0,58915$ for no intervention. in one out of ten simulated experiments, the end result of the :ans parameter varied minimally. All ten simulated experiments per condition are plotted in 3.4 but the single deviation is not visible.

This simple technical demonstration serves to prove how the :ans parameter can be modulated by varying the breathing rate in HumMod.

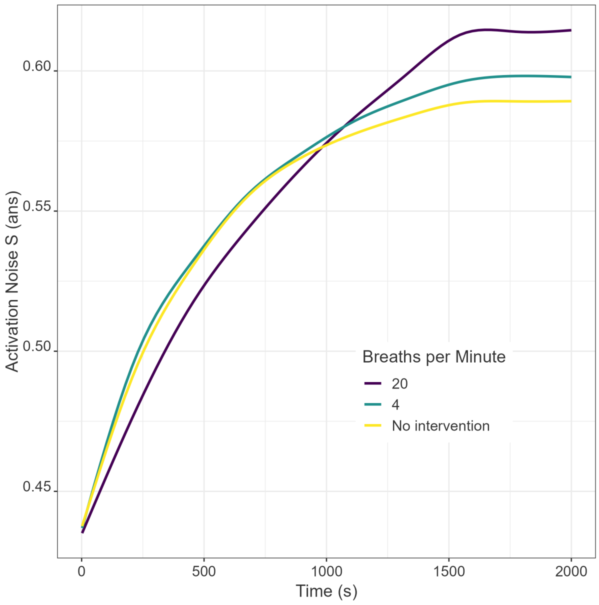


Figure 3.4: Plot of the activation noise s parameter :ans over time in three different conditions: Breathing rate set to 20 per minute, 4 per minute, or without intervention (ACT-R/Phi active). 10 model runs per condition.

3.6 Summary of the Chapter

In this chapter I discussed the practical implementation of ACT-R/Phi. To do this, I focused on the immediate interface between HumMod and ACT-R/Phi. The interface is the physiology system which consists of HumMod and the Physiology module created by Dancy.

The communication between HumMod and ACT-R/Phi is realized utilizing two text files, one file containing inputs from the Physiology module to HumMod and one file containing responses from the HumMod physiology simulation. Communication to HumMod primarily consists of setting variables to certain values in order to manipulate the physiology simulation as well as commands to advance the physiology simulation in time. It is also possible to load certain initial conditions into HumMod in order to set the physiology simulation into a desired state. Communication from HumMod primarily consists of lists of current values of the physiology simulation. During the setup stage HumMod also communicates a list of the variable names in HumMod. Subsequently HumMod returns the current state of these variables in the same order as the initial list. Once the Physiology module receives an updated list of HumMod variables it stores these values. Subsequent operations with the physiology values take place inside of the ACT-R/Phi modules.

Chapter 4

The Mind and The Body: MEi:CogSci and Philosophy

After discussing the ACT-R/Phi theory in Chapter 2 and diving into the computer implementation in Chapter 3, I will now take a step back and discuss the broader theoretical basis of ACT-R/Phi. What are the broader assumptions and questions researchers try to answer using cognitive architectures and what specific role does ACT-R/Phi take in this debate? Where does it try contribute and what is the general path forward regarding taking inspiration in the biology of living beings for understanding cognitive processes or even consciousness? Here, I shine my “MEi:CogSci Flashlight” onto the topic and relate the work by Dancy to broader discussions around the mind and the body. My aim in this chapter is to provide additional context and shed light onto the question, how ACT-R/Phi relates to current developments in cognitive science and philosophy (of mind).

4.1 The Philosophical Foundations of Modeling the Mind

> *"I've got to know how the gears clank, and how the pistons go, and all the rest of that detail."*
>
> *Allen Newell : Desires and Diversions : 1991 : Carnegie Mellon University*
>
> *—Allen Newell (2014, m. 11:00)*

In his famous 1991 lecture, Allen Newell lays out his personal motivation to understand the human mind. I am motivated similarly, and have personally taken interest in understanding how medium term decisions such as deciding on what to eat or deciding to exercise or not, or sleeping impact our phenomenal experience on one hand and our decision-making capabilities and processes on the other. The question whether we can actually figure out how our gears and pistons work is yet to be answered.

Underlying these questions are more general assumptions surrounding the nature of the mind. The biggest of them is the question, how the human mind relates to the human body. So before we can think about the mind as a machine as Newell suggests, I find it important to discuss what we need to concede in order to do so.

But what are the assumptions and discussions surrounding the general question that we try to understand the human mind by implementing it in a computer? Understanding the relation between physical matter and the mind has been the subject of discussion for a very long time. At the core, are discussions about the relation between the mind and the body. Allen Newell suggests the metaphor of mind as a machine: but is the mind a machine? And if it is what kind of machine and can it be built from cogs and wheels?

To help us with these questions, we can take a look at the philosophical debate around what is called the mind-body problem.

4.1.1 The Mind-Body Problem

The Mind-Body Problem is the name for the discussion around the relation between the human mind and the human body. Are mind and body two entirely different entities or does the mind simply emerge from the the body? I will introduce the main positions in the debate and will use them to lead us towards the philosophical foundations for creating computer models of the mind, such as a cognitive architecture. The aim of these philosophical inquiries into the nature of the mind is to serve as guidance towards choosing the right paths to follow when creating computer models.

On one hand is *Dualism* representing the claim that the physical manifestation of the human body and the human mind are made up of two distinct matters (Levin, 2022, p. 2). While not all dualists belive that the body and the mind are made up from different matters, they agree that there are certain configurations of matter – such as the brain – that are so complex that their states can not be reduced to physical states. (ibid.) Taking this position to an extreme would entail that arriving at an ever more detailed understanding of the brain will *not* lead to in increased understanding of the mind.

On the other hand is *Monism*, arguing that the mind is made up from the same basic building blocks as everything else in the world (Levin, 2022, p. 3). There are different positions within Monism and for the purpose of this thesis, *physicalism* is of particular interest. *Physicalism* states that the matter from which everything in the world is made up, is physical matter (Levin, 2022, p. 49). Since physicalism is a form of monism, this opens up the avenue of exploring the physical matter from which the mind is made up in order to explain the mind.

Functionalism takes physicalism a step further by suggesting that it is not the physical matter per se that makes up the mind, but the *function* fulfilled by the physical matter (Levin, 2022, p. 2). Focusing on the *function* of the physical matter, opens up the question whether the same function could be implemented in a different manner or a different substrate. In the study of the mind, we assume that the mind is implemented in a biological substrate. But we might think about how we could implement something that has the same function in a different substrate: for example on a computer.

The resulting idea, is that of *multiple realizability*: The position that the *functions* that make up the mind could – in principle – be realized in different physical substrates. The only requirement is that the *functions* that produce the mind are reproduced. As Allen Newell put it, we might want to think about building a mind using *"clanking gears"* and *"pistons"* (Newell, 2014, 11:00). For practical reasons, researchers have taken to implement the mind in silico – on a computer.

4.1.2 Summary of the Mind-Body Problem

Assuming that the mind is no different to everything else in the world, we study the matter which it is made up from (Monism). Assuming the matter which mind is made up from is physical, we study the physical universe (Physicalism). Assuming that physical matter fulfills a certain function, we think about the functions that implement the mind (Functionalism). And assuming that the functions need not be confined to biological systems, we try to implement these functions on the computer (Multiple Realizability).

Monism, Physicalism, Functionalism and Multiple Realizability are the general assumptions that serve as the philosophical foundations for the research on cognitive architectures. I will use these assumptions to contextualize the ideas making up and surrounding ACT-R/Phi. With this out of the way, I will now take a look at the target of contemporary research on understanding the mind: the brain.

4.2 The Relation between Mind, Brain and Body

> *Your head will collapse*
> *But there's nothing in it*
> *And you'll ask yourself*
> *Where is my mind?*
>
> *Where Is My Mind?*
> —*Pixies*

Where is our mind? The intuitive answer for many in our day and age is that it is in our brains. After some consideration, some might expand on this and start to include the entire central nervous system but the consensus would surely stop somewhere there for most. It is precisely the brain which has been at the center of investigation when it comes to explaining the mind. So much so that sometimes one could get the feeling that it is the only thing of interest when it comes to this investigation[1].

---

[1] This has not always been this way and the mind was for a long time investigated using techniques such as psychoanalysis. Discussing the split between current day psychology and psychoanalysis is beyond the scope of this thesis.

4.2.1 Mind and Brain

Within our bodies, the brain has been of particular interest and the object of choice for investigating the mind. Much of recent research inquiry into the nature of mind and cognition has put the brain into the center. The advent of functional neuroimaging methods such as functional magnetic resonance imaging (fMRI), functional electroencephalogram (EEG) and near-infrared spectroscopy (fNIRS) – to name three popular ones – allows researchers to peek into the functioning human brain non-invasively.

Andy Clark (2008) calls models, where the mind is set equal to the brain BRAINBOUND. Assuming this model is correct, it would be sufficient to understand neural activity in order to understand the mind. Since most neural activity happens in the brain, the brain is at the center of the BRAINBOUND model. The rest of the body is simply there to provide input for the brain and to serve the brain in interacting with the environment. But as we will see, not all lines of investigation equate the mind with the brain as I will discuss in Section 4.3.

4.2.2 Brain without Body

Imagine a brain, suspended in a translucent[2] container. Imagine that this brain is wired up and connected to a series of devices and cables that provide everything to the brain that it needs to operate. And now, imagine how this brain, suspended in a vat, is stimulated just in the right way, just expertly played by an orchestra of brain stimulators of the highest order where all the buttons are pushed in just the right order. This pushing of buttons would then succeed in producing the same exact phenomenal experience consciousness that one would experience in everyday life – with a twist: without a body.

Cosmelli and Thompson introduce this intuition pump of the "Brain in a Vat" (Cosmelli and Thompson, 2010; Thompson and Cosmelli, 2011). By discussing in detail the actual requirements of a human brain, they argue that everything *but* a body would be unable to meet the demands of our brains. For example, it would not suffice to simply provide the brain with oxygen rich blood but there would need to be a mechanism that would respond to the energy demands of the brain and precisely deliver the blood (and additional nutrients) to wherever they are needed. Our circulatory system is capable of just that precision. Following this argumentation, Cosmelli and Thompson thus say

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[2] For dramatic effect.

that our brains and bodies are so closely entangled that it is impossible to analyze them separately.

4.2.3 Body and Brain: Causal or Constitutive?

Before moving on I want to briefly discuss whether neural, and non-neural structures respectively, are causal or constitutive for cognition.

Causal factors are essential processes that are necessary pre-requirements for cognitive processes. But, these causal factors are in the background and can be thought of as constant when it comes to describing their role in enabling cognitive processes. Constitutive factors on the other hand are not only necessary for cognitive processes, they are at the "core of the thing in question" (Stapleton, 2011, p. 131f). Constitutive factors are the factors that we are interested in, to understand cognitive processes.

Neural processes are processes that happen inside of nerve fibers that are mostly located in the human brain – possibly including the central nervous system. Non-neural processes are processes that that happen *outside* of nerve fibers. This includes non-neural signalling mechanisms such as gasotransmission and changes in hormonal levels. (Stapleton, 2016, p. 17) also calls this the "gooey" realm.

The question then becomes, whether it is sufficient to look at neural processes or whether – given our more detailed understanding of the relation between the body and the brain – we must take all the non-neural processes that enable neural processing into consideration, too. This is an essential question and again, leads us to a difficult decision for modelers: what to include, what to exclude, where to draw borders and where to create interfaces. For the purpose of modeling, where decisions need to be made regarding the variables that are taken into account how can the insights into the tight entanglement of body and brain be of use for our purpose?

For my questions, the causal – constitutive distinction is aimed at the role of the "body" and that of the "brain" with respect to cognitive processes. Why is this question of relevance to my thesis? It is relevant because its answer will influence at which level of detail it makes sense to model the interactions between "body" and "brain".

If we were to take the approach from Cosmelli and Thompson seriously, there is little room to draw lines between mind, brain, and body. But, we are still interested in cognitive architectures and how enriching one with physiological data can help us make better sense of our selves. To resolve this issue I will now discuss approaches from 4E cognition.

4.3 Keeping the Body in Mind

Based on the arguments provided so far there are three points that appear to be central. Firstly, I laid out the philosophical assumptions requierd to model the mind in a different substrate. Secondly, I established that the main target of investigation for understanding the mind has been the brain. Thirdly, I introduced an intuition pump that appears to suggest that the relation between brain and body is tightly coupled, that looking at the brain alone is not sufficient for understanding the brain – and this not sufficient for understanding the mind. The question that follows is how and to which extent we should consider the body when concerned with understanding the mind.

Alternative approaches from cognitive science such as 4E approaches to cognition consider cognition to be Embodied, Embedded, Extended, and Enactive[3]. These approaches – and in particular the Embodied one – have plenty to say when it comes to the role of the body in making the mind. Embodied Cognition is concerned with the fact that human beings and animals are all grounded in physical bodies and is concerned with the question, how this fact shapes our cognition. And not only the fact that we have physical bodies, but also what these bodies are made up from: their internal embodiment.

4.3.1 The Embodied Mind

Embodiment is a paradigm in cognitive science that is concerned with the role of the body in cognition. In particular *strong* embodied cognition claims that the physical embodiment (having limbs, two eyes, ect.) that allows us to move and interact with our environment as well as anatomical (internal) embodiment (e.g. organs, the endocrine and circulatory systems, ect.) contribute to cognition (Gallagher, 2023, p. 10f). And that the nonneural body plays a significant role in pre- and postprocessing for the brain and shapes cognition (Gallagher, 2023, p. 11). Nevertheless, while the standard notion of embodiment gives

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[3] *Embodied* cognition is concerned with the role of the body (p. 5), *embedded* cognition with the role of the scaffolding provided by the environment (p. 14), *extended* cognition with the question where to draw the border between mind and external world (p. 18f), and *enactive* cognition with the role of action and the general action-orientedness of cognition (Gallagher, 2023, p. 30).

the body a bit of extra work by allowing for some pre- and postprocessing to happen, the brain remains central.

For some this does not sufficiently capture the role of the body in enabling the mind. For this reason, I will take a step further and introduce the notion of *proper* embodiment as brought forward by Stapleton (2011)[4].

4.3.2 *Proper* Embodiment: A Practical Compromise for Modeling?

Stapleton (2011) wrote her dissertation on *Proper Embodiment: The Role of the Body in Affect and Cognition* and continued on the topic further discussing the work of Cosmelli and Thompson (2010) in Stapleton (2016). At the core of Stapleton's work is an argument for *proper* embodiment: the need to think about "internal" embodiment, beyond the physical shape and makeup of a body (Stapleton, 2016, p. 17). Stapleton also calls this the "gooey" realm which is supposedly only taken seriously by enactive cognitive scientists, and not by embodimenters (Stapleton, 2016, p. 17).

The "gooey realm" contains about hormonal and other non-neural processes. Stapleton argues that these might not be taken seriously in a sense that this "gooey" stuff is mere implementation and thus should not matter. If it matters, this shakes the foundations of some of the assumptions we might have about the nature of cognition. Because, if the implementation (the substrate) matters, we need to take it into account. If we take this position to an extreme, the idea of multiple realizability might fall here[5]. The strong version of this argument would entail that it is a futile task building cognitive architectures in anything but biological systems.

A weaker position – which I would like to take here – is that yes, we need to take the "gooey" realm seriously and acknowledge the constitutive role of non-neural processes for cognition while also acknowledging that there is no way to implement this brain – body relation in silico. Nevertheless, simply accepting this position of proper embodiment requires us to take our understanding of the relation between body – brain – mind into

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[4] Mog Stapleton did her PhD at the University of Edinburgh under the primary supervision of Andy Clark (extended mind thesis).

[5] At the same time, perhaps it is still possible to model also the "gooey realm". The problem here becomes the old question: where to draw the line between what to model, and what not to model.

consideration when attempting to model the mind. That is, it is possible to utilize a silicone substrate to simulate processes of thought *and* take embodiment seriously. Of course this is limiting, but the aim of simulations and cognitive architectures is not to create 1:1 copies of humans but to create *useful* simulations.

This brings me to the next section, the notions of Levels of Analysis introduced by David Marr, and Newell's Time scale of human action, also known as Newell's Bands of Action.

4.4 Levels, Bands, and Layers

Now that I discussed the philosophical basis for modeling the mind and provided arguments that we need to take the body into account in order to understand the mind I will introduce two useful concepts that have guided work on cognitive modeling. The reason I do this is twofold. On one hand, these notions have guided the development of cognitive architectures and have been used to think about how to further develop cognitive architectures. On the other hand, the notions can help us in the impossible task to draw borders inside a system that I firmly believe can not be divided. Nevertheless, by breaking down problems of the mind between different Levels of Analysis and by looking at the timescale at which certain actions unfold, the notions introduced by Marr and Newell help modelers to draw lines, but also to think about the ways in which different levels are connected[6]

The notion of Levels of Analysis by David Marr (2010), in which he suggests breaking down complex systems into three levels in order to tackle them more systematically. And, the notion of Bands of Action, in which Allen Newell (1990) suggests that we can think about different aspects of the mind by looking at different timescales.

It is important to remember that these are abstractions. I would not think of them as dogmatic in the sense that these are the *only* ways to think about cognitive architectures. But, it must be said that these notions are highly influential for a good reason: they help one to think about cognition at a certain level or inside of a band of time. These abstractions are the lifeblood of anyone who wants to model complex phenomena, as

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[6] For example: what is the nature of the interface between the Hardware and Algorithmic Level? Marr advocated not only for thinking across three Levels, but also for clearly specifying interfaces between these levels! I will return to the point of the nature of the interface between body and mind in Chapter 5.

without abstractions, without boundaries, we would be lost.

Scale (sec)	Time Units	Level of Analysis (Marr)	World (theory) (Newell)	System	Emotion System
10^7	months	Computational	Social Band	(Expertise)	Expressed & Interpreted
10^6	weeks	Computational		(Culture)	
10^5	days	Computational		(Culture)	
10^4	hours	Computational and Algorithmic	Rational Band	Task	Act
10^3	10 min	Computational and Algorithmic		Task	
10^2	minutes	Computational and Algorithmic		Task	
10^1	10 sec	Algorithmic and Hardware	Cognitive Band	Unit task	
10^0	1 sec	Algorithmic and Hardware		Operations	
10^{-1}	100 ms	Algorithmic and Hardware		Deliberate act	
10^{-2}	10 ms	Hardware	Biological Band	Neural circuit	Emerge
10^{-3}	1 ms	Hardware		Neuron	
10^{-4}	100 μs	Hardware		Organelle	

Table 4.1: Newell (1990)'s Time scale of human action and Marr (2010)'s Levels of Analysis as summarized by Lieto et al. (2018). Extended to include emotion based on Larue et al. (2018).

4.4.1 David Marr's Levels of Analysis

David Marr's seminal work *Vision* has had profound influence on the field of cognitive science (Marr, 2010). Marr proposed three Levels at which we need to understand complex information processing system: Computational Theory, Representation and algorithm, and Hardware implementation (ibid. p. 20). Besides understanding each of these levels, the explanations need to be linked and internally cohesive (ibid.).

When we think about ACT-R/Phi, Dancy takes inspiration in the physiological, the "hardware implementation" of humans but especially looking at the brain. Dancy's contribution is to think about how the level of hardware implementation can inform the level of representation and algorithm. In my understanding, the approach of David Marr is a differentiation on the spatial level/spatial resolution.

4.4.2 Allen Newell's Bands of Action

Allen Newell's thinking was guided by Time. He proposes four bands of action[7], functioning at various timescales from 10^{-4} to 10^{7}. The bands are the biological band, the cognitive band, the rational band, and the social band (Newell, 1990, p. 122). Now what Newell does here is very elegant,

If we look at the bands that ACT-R covers, we can think in terms of them when thinking about the influence of the biological band on the cognitive band.

In a sense I understand the work of Dancy to be of such kind that tries to take the mounting evidence on the interconnected between Marr's layers: How much does the hardware implementation matter for the higher levels? And the mounting evidence of how processes in the biological band influence the cognitive band. In my understanding, Allen Newell's approach is a differentiation on the temporal scale.

4.4.3 Levels and Bands of ACT-R/Phi

Now that we introduced Levels and Bands I provide my take on placing ACT-R/Phi within them. For this purpose I attempt to present Marr's Levels of Analysis side by side with Newell's Bands of Action in Table 4.1. My aim is to show how these concepts overlap and can be used side by side to inform thinking about modeling the influence of physiology on cognition.

ACT-R/Phi thus does two things: Firstly, The modules that make up ACT-R/Phi are implemented in a way that they can operate outside of the 50ms processing cycle of ACT-R. From the perspective of Newell's Bands of Action, ACT-R/Phi extends ACT-R further down into the Biological Band. For example, the processing of affective information embedded in picture stimuli happens outside of the 50ms processing cycles of ACT-R. This way information about processes happening at the Biological Band can be used to influence process at the Cognitive Band.

Secondly, by taking multiple physiological variables to modulate *noise*, ACT-R/Phi increases its spatial resolution. I understand this as an attempt to specify the interface between the *Hardware implementation* and *Representation and algorithm* Levels in greater

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[7] Newell expands this to add two more bands: the historical and evolutionary bands. These additional bands are not relevant for our purpose. You can find a recent version including all six bands by Newell in Lieto et al. (2018, p. 759)

detail. A higher resolution interface between these two Levels allows for a more accurate model of the actual relation between body and mind.

Based on the discussion around the role of the body for the brain in Section 4.2.2 and the corresponding discussion around *proper* embodiment in Section 4.3.2 the lines between what I understand to be the *Hardware implementation* and *Representation and algorithm* begin to blur.

Here I attempted to ground the ACT-R/Phi processes in the Levels of Marr and Bands of Newell while appreciating the complexities of the reality of mind, brain, and body relations.

4.5 Building Bridges from *within*: Micro- and Neurophenomenology

> "9. Begin to search for the neurophysiological counterparts of the elementary information processes that are postulated in the theories. Use neurophysiological evidence to improve the problem-solving theories, and inferences from the problem-solving theories as clues for the neurophysiological investigations."
>
> *Human Problem Solving: The State of the Theory in 1970*
>
> —Herbert A. Simon and Allen Newell (1971, p. 146)

Expanding on the opening quote, Simon and Newell sketch out a plan for how research in "Human Problem Solving" can progress over time. When it comes to linking psychological explanations of "information processing" they can not see the direct link between explanations on the neurophysiological level (biological band) and explanations on the psychological level (rational band). What they suggest, is to use psychological theories to aid the neurophysiological discovery process.

In 1970, Simon and Newell (1971, p. 157f) couldn't *"see the bridges between the central nervous system [...] and the components of the information-processing system..."*. But this need not be the case anymore today. Psychology, cognitive psychology but perhaps more clearly neurophysiology progressed immensely in the last decades as we shall see and a bridge between the central nervous system and information-processing systems might actually be visible. Research in neuroscience is starting to describe in ever more detail the complexities of neuronal signalling and other means of signal transmission[8]. Research in (the) affective science(s) describes the intricate interactions between affective and cognitive processing mechanisms and questions the idea that these processes can be thought of as separate. Research in (the) cognitive science(s) attempts to integrate these findings and build a solid foundation based on enaction and forms of embodiment. Because of these developments, I believe that the bridges between the central nervous system and components of the information-processing system are becoming visible. And I believe that ACT-R/Phi is precisely such an attempt at consolidating evidence this more detailed understanding of the central nervous system and the components of the information-processing

An interesting discovery was that some of the basis for the work on the General Problem Solver (GPS) was the use of verbal *"think-aloud protocols"* (Newell and Simon, 1972). During these protocols, subjects would talk aloud while they were e.g. contemplating their next chess move. These *"think-aloud protocols"* employed by Newell and Simon[9] focus on the subject explaining[10] their cognitive processes while solving a task. Newell and Simon would use these protocols to develop general theories about problem solving, eventually resulting in the General Problem Solver.

These *"think-aloud protocols"* remind me of the work on microphenomenology and neurophenomenology. Microphenomenology (c.f. Petitmengin (2006)) is an interview technique that aims to methodologically deconstruct individual phenomenal experience into smaller pieces across spatial and temporal dimensions. The aim of microphenomenology is to leverage the capacity of individuals to describe their subjective experience in high detail when questioned in a specific way. Multiple microphenomenological interviews on the same experience with different subjects might reveal a higher resolution picture of a phenomenon of interest. Neurophenomenology takes microphenomenology a step further by adding neuroimaging to microphenomenological interviews. In Neurophenomenology,

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[8] See for example our evolving understanding of the role of glial cells.

[9] Developed by Ericsson and Simon (1993).

[10] As opposed to a cognitive neuroscientist scanning the brain of a chess player and simply having neural data and the move that the player eventually selected.

brain activity is recorded but instead of only trying to correlate brain activity with results from a behavioral experiment, an expert interviewer could ask the co-researchers (participants) about their experience during the experiment in a way that could enhance the level of detail available to make sense of the neural – or other physiological – data.

The microphenomenological approach brings the embodied experience of individual co-researchers to the center. I would propose that this approach would also lend itself to the exploration of the role of physiological change on phenomenal experience and could provide promising avenues or research towards exploring the mind-body relations: ethically and non-invasively. I believe that neurophenomenological and microphenomenological investigations – that include expert interviewers as well as experts in observing and explicating their own internal functioning – could very much aid the process of better understanding the intricate interplay between body and mind.

4.6 Summary

In this chapter I introduced the mind-body problem and how it relates to attempts to create cognitive architectures. I discussed the relation of the brain and the body and brought in discussions from embodied and enactive cognition. In a next step, I introduced the notions of Levels of Analysis and Bands of Action as guiding frameworks for thinking about modeling cognition and attempted to relate the work in ACT-R/Phi to the Levals and Bands. Finally, I picked up a task that Simon and Newell discussed: the task to use *"neurophysiological evidence to improve problem-solving theories"*(Simon and Newell, 1971, p. 157). Modern neuroimaging techniques and sophisticated wearable sensors allow researchers to measure human physiology at a higher spatial and temporal resolution than fifty years ago. Interview techniques from the micro- and neurophenomenological tradition can supplement data gathered from neuroimaging and physiology measures to provide a more detailed account for the relation between subjective experience, behavior and physiology.

Chapter 5

The Mind and The Body: Physiology – Affect – Cognition

The aim of this chapter is to discuss the relation between physiology, affect, emotion, and cognition as these concepts relate to ACT-R/Phi[1]. In particular it is my goal to discuss specifically how the interface between physiology and cognition in ACT-R/Phi was bridged using the theory or *primary affect* by Jaak Panksepp (2004).

Furthermore, I will contextualize primary affect by introducing discussions around the current state in emotion research from a theoretical perspective as well as discussions around the relation between cognition and emotion from a cognitive neuroscience perspective.

Finally, I will relate the discussion around physiology, affect, emotion, and cognition to the discussion around the role of Emotion in the Common Model of Cognition.

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[1] In the early stages of my thinking about this thesis, "emotions" only entered my thoughts as an afterthought. The picture I had in mind was that it would be easy enough to simply connect some physiological measures to ACT-R parameters. I did not start to think about how these physiological values would need to be transformed or to which ACT-R parameters they could be tied in a principled manner until after I started to engage with ACT-R/Phi closely. And this is despite the fact that affect is central to Dancy's dissertation. It is safe to say that I was naive towards the role of emotion and affect even after I decided to write my thesis on this topic. Even as I came around to appreciate the role of affective science as a blueprint for understanding the relation between physiology and cognition I feel like this is the area I know least of as I conclude this thesis. My lack of depth in understanding of the topic of emotion remains evident and is also due to the fact that I did not attend any courses on the topic as part of my studies and did not have the resources to fill this gap as part of my master's thesis.

5.1 Emotion in ACT-R/Phi: Primary Affect

Dancy follows a conceptual separation of research into emotion into three perspectives, physiological-anatomical, cognitive, and social (Dancy, 2014, p. 11). In his overview of the field Scherer (2022) differentiates between three types of emotion theories: Basic emotion theories (including physiological-anatomical), appraisal theories (cognitive) and constructivist (social) theories (p. 161).

5.1.1 Affect

The basis for bridging the physiological and the cognitive for Dancy's work on ACT-R/Phi is the theory of *primary affect* developed by Panksepp (2004).

Panksepp founded the field of affective neuroscience which *"broadly refers to the study of the neural bases and correlates of emotion and related affective phenomena"*(Davidson, 2009). Panksepp (2004) specifically proposes that there are primary affective systems which correspond to distinct hardwired brain circuits. Panksepp and Biven (2012) mapped out the brain circuits corresponding to proposed primary affective systems based primarily on research in rodents. Subsequent neuroimaging studies enabled the mapping of primary affective systems to activation in specific brain areas (Dancy, 2014, p. 14). This is the crucial connection that enabled Dancy to match physiological values to affective states and to use simulated physiological values to modulate ACT-R parameters.

Panksepp and Biven (2012) posited and worked on associating primary affective systems that correspond to distinct neural *circuits* and cause unconditioned behaviors when activated (Dancy, 2014, p. 14). In the Handbook of Emotions Scarantino (2016) states that the debate whether distinctive neural circuits for basic emotions exist is not resolved (p. 40).

In their review of concepts and definitions of emotion, Cowie et al. (2011, p. 13) describe the understanding of affect by Panksepp as a feeling state (that need not be conscious)that correspond to a physiological state. This is a crucial position as it opens up the possibility to measure a persons affective state based on physiological measures. In the case of Panksepp, his focus was on finding neural *circuits* corresponding to affective states. The theory of *primary affect* is a *circuit* theory of emotion.

5.1.2 Circuit Theories in Context

Understanding affective states to be rooted in neural circuits is central to the search for the physiology corresponding to these affective states. Where do circuit theories of affect fit within the affective sciences? Affect is covered from many perspectives with different foci. Basic emotion theorists state that there are several types of emotions that are *"rooted in discrete physiological systems."*(Cowie et al., 2011, p. 28). Panksepp and Biven state that primary process affective systems (primary affect) cause unconditioned behaviors (Dancy, 2014, p. 14).

To summarize, primary process affect is Panksepp et. al.'s version of a circuit theory of emotion which is a type of basic emotion theory. Circuit theories attempt to find the neural circuits associated with basic emotions, and basic emotions are emotions that are rooted in evolution and discrete physiological systems.

5.1.3 Why Primary Affect? Why FEAR and SEEKING

Examples for these primary affective systems are the SEEKING and the FEAR systems. Dancy focuses on the SEEKING and FEAR systems because they have been studied widely (Dancy, 2014, p. 14).

5.1.4 Primary Affect, Neural Circuits

In their *"authoritative summary of major emotion theories"*[2],Scarantino and de Sousa (2021, Section 11.4) conclude that there is agreement regarding the seat of emotion in the brain. The debate whether distinctive neural circuits for basic emotions exist is not resolved (Scarantino, 2016, p. 40). Scarantino and de Sousa (2021) state that *"there are no neural circuits that correspond one-to-one with any folk emotion type"* (Section 11.4).

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[2] (Scherer, 2022, p. 165)

5.2 Other Approaches Linking Physiology and Cognition

5.2.1 Core Affect

The concept of core affect (Russell, 2009) (from the family of constructivist theories) is an interesting candidate for continued exploration based on Juvina et al. (2018)'s implementation of core affect in ACT-R. Juvina et al. (2018) implemented core affect without a connection to physiology but suggested their model could benefit from grounding in physiology (p. 21).

Core affect is defined as a neurophysiological state that is available to consciousness (Russell and Barrett, 2009). Core affect is made up of two dimensions: valence, which is feeling good or bad; and arousal (or activation) which is feeling drowsy or energised (Russell, 2009, p. 1259). The concept of activation is of specific interest to us. Activation is defined as an attribute of representational units that varies from weaker to stronger (APA Dictionary of Psychology, 2018). These representational units then compete to control processing. Activation is implemented in ACT-R as the :ans parameter (activation noise s) and it is one of the parameters modulated by physiology in ACT-R/Phi.

Based on the definition of core affect as a neurophysiological state the question becomes whether core affect can be grounded in physiology.

Grounding Core Affect in Interoception and Physiology

Mog Stapleton argues that core affect is grounded in interoception. Stapleton then sketches out how the two components of core affect – arousal and valence – are grounded. Arousal is grounded in sympathetic nervous system activity (Stapleton, 2011, p. 101). Valence is grounded in the motor aspects of the homeostatic loop (p. 102f). Conceptualizing affect in this way allows us to look directly at the target of interoception: physiology that we can in our case directly read out from HumMod. So in a sense, affect is the first layer of abstraction integrating the information of the body.

The next step would be to identify fitting variables in HumMod that would serve to ground arousal and valence. If arousal is sympathetic nervous system activity, it could simply be "Vagus Nerve Activity" in HumMod.

Finding an appropriate variable in HumMod to represent valence is tricky. But, if valence is the motor aspects of the homeostatic loop, it could be a measure based on various motor activity or metabolic activity in certain body regions that are available in HumMod.

The question thus is, is whether grounding affect in physiology would help with the aforementioned issue of overfitting/underconstraining. If we agree that affect can be grounded in physiology following argumentation from Stapleton (2011, p. 94–). We can than set out to find good candidates for physiological markers of affect that are well represented in HumMod, can be tied to ACT-R Parameters and are also directly/indirectly measurable in humans for the purpose of validation and verification.

Screening HumMod variables to represent valence and arousal to implement physiology based core affect could be a way to utilize ACT-R/Phi in an explorative manner.

5.2.2 Inspiration in Physiology: Action Oriented

> *"First, behavior requires a body. Disembodied behavior is not possible. Both animals and robots have bodies that are capable of intelligent behavior, and can influence the world around them. An intelligent computer that has no body and that cannot influence its environment, is not capable of intelligent behavior."*
>
> *—McFarland and Bösser (1993, p. 1)*

During my investigations I discovered two general motivations why researchers decide to add a body or bodily functions to their models.

First there is the cognition oriented (top-down) approach that starts out with investigating the mind and mental phenomena and eventually and tries to ground findings about the mind in the physical reality in which mind is implemented. The cognition oriented approach aims to add a body in order to be able to compare model performance with human performance. ACT-R in general, and ACT-R/Phi in particular are examples for this category.

The second approach that I will briefly introduce here is the action oriented (bottom-up) approach which is concerned with the (engineering) challenge to produce agents that are capable of intelligent adaptive behavior. This perspective to the topic of physiology –

emotion – cognition[3] comes from robotics. Researchers interested in creating robots capable of adaptive behavior have taken inspiration in animal (including human) physiology. This approach is the "Animals to Animats"[4] approach in which researchers take inspiration in animals (and animal physiology) for thinking, simulating and building artifacts ("Animats") that are capable of solving tasks in the real world.

A very elegant early example is that of Valentino Braitenberg (1986)'s Vehicles[5]. Braitenberg's vehicles – little robots with wheels and sensors – exhibit a wide range of behaviors using very simple components. Analyzed from the outside, humans might assume that these vehicles operate with great sophistication. In reality they only utilize a couple of sensors (e.g. light, temperature, oxygen concentration, ...) connected to two motors (turning a wheel either forward or backward). As soon as different types of sensors and external sources (e.g. light) are combined, these robots can exhibit a wide variety of behaviors.

In this vain, researchers took inspiration in animals (including humans) to model behavior in robots. For my purposes, I will focus on approaches that are inspired by animal physiology. This includes hormones but also more abstract measures such as hunger, thirst or the need for warmth.[6] Importantly, the implementations are abstract and don't necessarily correlate 1:1 with a physiology measure: I understand these as functional abstractions.[7] The hormonal systems don't immediately depend on sensory input. They can represent the internal state of a robot and change on a different timescale than sensory input (Gadanho and Hallam, 1998, p. 358).

This action oriented approach, since they provides a complementary approach to the cognition oriented (top-down) approach of ACT-R and I think it is worth reflecting on the similar issues covered from these distinct camps as I understand them.

The bottom up approach, which is robotics oriented and tries to simulate and build robots that are capable of performing certain tasks had a different approach: robots by

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[3] Perhaps more aptly called implementation – modulation – behavior in this context

[4] c.f. the Proceedings of the International Conference on Simulation of Adaptive Behavior "From Animals to Animats".

[5] An even earlier and perhaps more complex example comes from Toda (1962) in which he attempts to design an agent (a fungus-eater) around the environment it has to survive in.

[6] Again I am thinking about the ontogeny of emotion and its potential grounding in "primary metaphors" c.f. Grady (1997).

[7] One example would be to equate one hormone with one feeling (Gadanho and Hallam, 1998, p. 355).

definition have a “body” and controlling this body and “making it act” in the world in a certain way is the whole point. Researchers in this domain have always looked for inspiration in nature: be it the physical shape of the robots in relation to the task they should accomplish but also in relation to their “internal control system”, their embodiment. Some of the researchers in this area have experimented with simulating hormone like substances to control robots (Avila-García and Cañamero, 2004). Other researchers have simulated neural network with additional ways of transmitting information in a diffuse manner such as Gasotransmission (GasNet) (Stapleton, 2011, p. 143).

Curiously, It appears to me that research from both of these areas appears to be converging towards a better representation of “internal embodiment” as a way for a) robots to adapt to task environments better across different timescales and b) cognitive architectures having to reflect the increasing evidence of the importance of non-neuronal processes on cognition and trying to account for physiological measures.

5.3 The Relation between Emotion and Cognition

The question how emotion and cognition are related, and whether they are two distinct entities or inseparable, is as old as the question about the relation between the body and the mind. On one hand Plato suggested that there is a strict division between cognition and emotion (Scherer, 2000, p. 142). A notion that influenced *“philosophers and psychologists for over two millennia”* (ibid.). Aristotle on the other hand argued that cognition and emotion were inseparable (ibid.).

One could say that there is a cognition–emotion problem to accompany the mind–body problem. Fittingly, cognition is often related to the brain (as the seat of mind) while emotion is related to the body.

Dual-system models for example propose that there are distinct systems: System 1 (fast and heuristic driven, emotional) vs. System 2 (slow and deliberate, cognitive) and proponents have suggested, that these systems are implemented in different brain areas. System 1 in subcortical areas and System 2 in prefrontal cortical brain areas (Moors, 2022, p. 25). Empirical evidence summarized by Moors (2022, p. 25f) heavily questions dual-system models by showing that rule-based reasoning can happen very fast, suggesting there is one single system which operates more quickly/slowly because of different levels of complexity, and not because tasks are divided into two systems across the brain.

Moors (2022) also introduces Panksepp as a proponent of a triple-system model which serves as the basis for ACT-R/Phi in which primary processes, secondary processes and tertiary processes are distributed across the brain and operate distinctly (p. 26). A popularized version of a triple-system model are also so called theories of the triune brain in which the brain is divided into three parts: a "reptilian" brain responsible for instinct & survival, the "limbic system" home of emotions, and the neocortex: where higher level processing takes place (MacLean, 1973). (Feldman Barrett, 2020, p. 10) suggests that this theory does not hold up to scrutiny and (Moors, 2022, p. 26) implies that triple-system models have not been tested empirically (p. 26).

A recent discussion of the relation between cognition and emotion comes from modern day cognitive neuroscientists. Prominent figures in the field such as Pessoa, Damasio and LeDeoux research the fundamental role of affect in cognitive processes, as pointed out in Stapleton (2013, p. 7). Pessoa (2015)[8] goes so far as to paint a picture where emotion and cognition are so tightly intertwined that it is impossible to tease them apart. This is in contrast to Panksepp (1990), who argues that we need to understand (mechanistically) emotion processes first in order to understand cognitive processes.

Pessoa (2015) rests his arguments for the entanglement of cognition and emotion on criticism of early neuroimaging studies. These studies claimed to show more activity in certain brain areas compared to others when processing emotional stimuli which led researchers to label certain brain areas as emotional (p. 5). Pessoa argues that increased activity in certain brain regions can be explained in at least three ways: *"greater capacity to utilize the region, neural inefficiency, or increased effort"*(ibid.). Therefore, labeling certain brain areas as emotional based on increased brain activity is not warranted.

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[8] Pessoa uses neuroimaging techniques to study how cognition and emotion interact.

5.4 Emotion in the Common Model of Cognition

> *"Clearly, I can't mean a theory of all that! A unified theory of cognition is just a fantasy."*
>
> *Human Problem Solving: The State of the Theory in 1970*
>
> —Allen Newell (1990, p. 16)

Attempts of modulating the performance of cognitive architectures using concepts from research in the affective sciences is not a new approach. An early mention of emotion in a model of cognition is in the book "Unified Theories of Cognition" by Allen Newell (1990, p. 16). Marinier III (2008) attempted to integrate a model of emotion into the Soar cognitive architecture (also summarized by Laird (2008, p. 7f)) and Juvina et al. (2018, p. 5) attempted to model emotion in ACT-R based on the concept of *"core affect"* which they state to be a *"more primitive and more general"* than emotions.[9]

Initial attempts to reach a consensus around the role of emotion in the Common Model of Cognition are summarized in Larue et al. (2018) but did not appear to continue for a while.

In his memoir, Paul Rosenbloom mentions that (at the time) he, Christian Lebiere, John Laird, und Andrea Stocco met biweekly to discuss and work on the Common Model of Cognition (Rosenbloom, 2023, p. 32f). Out of these meetings Rosenbloom, Lebiere, Laird and Stocco organized an online workshop to discuss the role of Emotion in the Common Model of Cognition in 2022 (Rosenbloom et al., 2024, p. 2). Since they did not reach a satisfying consensus, a subgroup of the workshop participants got together to further develop their ideas around the role of Emotion in the Common Model of Cognition. This group presented their latest contribution a the 2024 ICCM conference where they propose the addition of a *emotion* module[10] to the Common Model of Cognition (Rosenbloom et al., 2024, p. 160).

What is very interesting for the purpose of this thesis, is that all publication on the topic of Emotion in the Common Model of Cognition stress the importance of grounding

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[9] Another early attempt to model the effects of emotions is the work by Velásquez (1996); Velásquez and Maes (1997); Velásquez (2007)

[10] The authors decide to label the module to *emotion.* It has previously been labeled as physiology, affect, or emotion (p. 160).

emotion in physiology (Rosenbloom et al., 2024, p. 160f), or being neurophysiologically plausible (Larue et al., 2018, p. 743). However, the details regarding which aspects of physiology would be used as input for the emotion module, and how these aspects would be transformed are not sketched out. This leaves us with open questions: how would the implementation of the physiology and emotion part of Common Model of Cognition look like? What would take the place of physiology: HumMod or something else? Which aspects of physiology would be used as input for the emotion module? How would the physiology in the emotion module be transformed? How would the emotion module influence the rest of the modules?

5.5 Summary

Dancy chooses to work with primary affect for practical reasons, but the theory is not without its critics who question the presence of distinct hard-wired neural circuits for emotion. In his dissertation Dancy stresses the importance of having a unified theory of human physiology and a unified theory of cognition to create a computational theory of affect and emotion (Dancy, 2014, p. 17). However, a unified theory of affect and emotion would be useful for this purpose, too. Scherer (2022) attempts to summarize the state of convergence within emotion theory and suggests, that while the field might appear to be divided, there appears to be a clear path forward towards convergence.

Chapter 6

Discussion – Assesment – Reflection

In this last chapter, I will discuss the reception of ACT-R/Phi by the research community. I will further reflect on the impact of ACT-R/Phi in a broader sense as well as on potential uses of ACT-R/Phi that have not been realized (yet).

Second, I will reflect on the general challenges for cognitive architectures and the potential additional challenges that arise by adding a second independent software component as is the case for ACT-R/Phi.

Third, I will reflect on the aims I had for this thesis and what I did and did not achieve while working on this project. I will try to express what I knowingly did not cover as well as the aspects that only arose during the work on the thesis and I was not able to cover because of the constraints of this project. I will address the strengths and achievements as well as the limitations and shortcomings of this thesis.

Fourth, I will reflect on the question whether I did manage to "lay down a path in walking" i.e. whether and what I achieved by attempting to write this thesis with my interpretation of Varela et al. (2016) in mind.

Finally, I will conclude this thesis by summarizing my contribution and concluding with my final thoughts.

6.1 Reception of ACT-R/Phi

To assess the impact and reception of ACT-R/Phi I conducted a citation analysis using Web of Science (WoS), Scopus and Google Scholar to find articles that reference Dancy's work on ACT-R/Phi. I conducted the citation analysis on the May 7, 2024 and obtained

186 articles. I screened the articles for relevance based on abstract and identified two ways in which I believe it is relevant to discuss the reception of ACT-R/Phi.

First, I will discuss the applied relevance of ACT-R/Phi: Dancy and other researchers using ACT-R/Phi directly, building on core concepts of ACT-R/Phi or using ACT-R/Phi as direct inspiration for their personal approach. Second, I will to discuss the broader impact of ACT-R/Phi in particular with respect to efforts to add Emotion to the Common Model of Cognition. Third, I will reflect on potential uses of ACT-R/Phi beyond the intended purpose of modeling human behavioral data in more detail by accounting for physiology.

6.1.1 ACT-R/Phi and the Common Model of Cognition

I believe the most obvious and important contribution of ACT-R/Phi is by adding to the discussion around the role of emotion in the Common Model of Cognition. Related to this, Dancy co-authored two articles. In the first round of contributions to the Common Model of Cognition[1], Dancy and Ritter argue for the need of a “body” for a Standard Model of the Mind in order to interact with the world and account for the energy needs of the brain (Dancy and Ritter, 2017, p. 316). In the second round of contributions to the Common Model of Cognition Dancy contributed to an article titled “Emotion in the Common Model of Cognition”(Larue et al., 2018). In it the authors argue for the need for a model of emotions to be neurophysiologically plausible (p. 743). Here the authors rely on ACT-R/Phi as an example. After the public discussion in form of publications quieted down, Rosenbloom et al. (2024) brought fresh wind by sketching out more clearly how a Emotion module might look like in the Common Model of Cognition. Rosenbloom et. al. propose that the Emotion module should receive input from physiology and also refer to ACT-R/Phi as their example for this (p. 160).

I will now engage with the themes in which ACT-R/Phi was referenced in an attempt to shed light on the impact and importance of ACT-R/Phi.

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[1] Still called “Standard Model of the Mind” at that time.

6.1.2 Inspiring Research in Japan

> *"Things are easy when you're big in Japan"*
>
> *Big in Japan —Alphaville*

During my research I discovered multiple relevant publications referring to ACT-R/Phi from the Applied Cognitive Modeling Lab headed by Junya Morita from Shizuoka University, Japan[2]. Work from Itabashi et al. (2020) takes inspiration in ACT-R/Phi and modulates the ans (activation noise s) parameter in ACT-R using Heart Rate Variability (HRV). It is a quite elegant connection, updating the ANS parameter every 6 seconds based on the standard deviation of NN intervals of Heart Rate (p. 95). Increased HRV (associated with a relaxed state) leads to increased noise which will lead to more variety in memory retrieval. Lower HRV causes lower noise and goes more towards rigid, repetitiive, "ruminative" memory recalls. A subsequent publication from the lab deals with "regulating ruminative web browsing" based on HRV (Morita et al., 2022).

Nagashima et al. (2022) from the same lab make it explicit, that their work was inspired by ACT-R/Phi. Nagashima et. al. point out what they believe to be an issue with ACT-R/Phi: by having to account for two simulation systems (ACT-R and HumMod) they state that ACT-R/Phi has a *"unification problem between cognitive and physiological processes"* (p. 200). In order to overcome this, the authors set out to model the physiological mechanisms modulating the ANS parameter directly inside of ACT-R by utilizing the *temporal module*, eliminating the need for HumMod.

I believe these approaches coming out of the lab of Junya Morita in Shizuoka to be the most honest attempts at taking what Dancy is getting at with ACT-R/Phi and building on it.

6.1.3 Potential Applications

Besides the role of ACT-R/Phi in the discussion around emotion in the Common Model of Cognition and reseachers taking inspiration in ACT-R/Phi directly there is a third category of interest and that is the question how ACT-R/Phi could be used.

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[2] Morita visited Frank Ritter at Penn State University in 2010 (`https://www.frankritter.com/ritter-vita.pdf`, accessed 2024-09-14)

ACT-R/Phi to Simulate Diversity

Prather et al. (2022) pose the question what cognitive science can do for people. In this article co-written by Dancy the authors discuss the issue that the majority of experiments focus on a WEIRD (Western, Educated, Industrialized, Rich and Democratic) population. While cultural influence can be thought of as a "top-down" type of modulation, culture might also create distinct "bodies". Could ACT-R/Phi can play a role in rectifying the WEIRD population sample bias by simulating a wider variety of "bodies" using HumMod?

Larue et al. (2022) bring forward the idea that computational models of the mind should strive towards populational realism and take into account neurodiversity (p. 176). Often times participants from groups outside of the established norm are not taken into account when conducting experimental research.

Which role could ACT-R/Phi and related approaches play in simulating a more diverse populations that can not be recruited for psychological experiments?

ACT-R/Phi as an Explorative Framework

Morse and Ziemke suggest that one use of cognitive architectures is exploration (Morse and Ziemke, 2008, p. 37). Exploration – in contrast to sufficiency and necessity, which are concerned with accounting for e.g. data in human experiments – is a theory driven, modeling first approach (ibid.). Morse and Ziemke propose to use exploration modeling to test theories about the role the environment plays in shaping agent development (ibid.). While the authors are concerned with the external environment, I propose that we could – in the sense of Stapleton's proper embodiment – turn the lights on the internal environment, too (Stapleton, 2011). This would allow us to investigate, in a theory driven manner, the interactions between the internal environment of an agent and its development.

This explorative approach could allow for safe and ethical exploration of hypothesized connections between internal environment (physiology) and cognition. Experimentation in humans would only follow after successful models have been developed. A possible intermediary step would be to test models in embodied robots before human experiments.

Experiments with human participants are time and resource intensive and require ethical approval and care – especially when more intrusive methods such as pain stimulation or administration of certain pharmaceutical compounds are applied. Solidifying theory in simulation and in (internally and externally) embodied agents before going into experimentation with humans would thus help to guide human experiments and ensure that the most is made out of them when they are applied[3].

6.1.4 Future of ACT-R/Phi

The further development and future of ACT-R/Phi is not clear. There are multiple hints that work on ACT-R/Phi is planned based on Dancy's Grants awarded by the NSF as communicated through his personal homepage NSF Grants/Dancy THiCC Lab Homepage. NSF Awards: 2144887 (CAREER: SocioCulturally Competent Agents to Study and Improve Human-AI interaction), 2229881 (AI Institute for Societal Decision Making (AI-SDM)) In a discussion at the 2023 ACT-R Workshop Dancy mentions work towards representing Social Band issues in ACT-R (Attendees of the "Future of ACT-R" Session at the 30th annual ACT-R Workshop, 2023, from 51:30). Taken together with ACT-R/Phi, this would result in an ACT-R version that incorporates bottom-up modulation through affect and physiology as well as top-down modulation through a semantic network.

While these are indicators that ACT-R/Phi might be developed further, I was not able to identify a new model or publication based on ACT-R/Phi models during the work on this thesis.

6.2 The Trouble with Modeling the Mind

One more topic that I feel the need to address is centered around general questions related to modeling the mind. In some sense the modeler is at a dilemma. On one hand, is the impossibility to draw a clear line between e.g. body and mind as soon as we focus on the many connections between the two. On the other hand, there is the absolute necessity to abstract away from reality in case we want to understand basically anything. There is a need for abstraction which is in constant competition with the desire to break down and explain in detail. There is a constant negotiation of the borders between what to make explicit, and what to (explicitly) ignore.

Following the discussion of the "Brain in a Vat" in Section 4.2.2, it may be intuitive

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[3] c.f. the National Centre for the Replacement, Refinement and Reduction of Animals in Research (NC3Rs).

to see how broadly the body and the brain are connected. But when it comes to *modeling* the relation between body and mind, things become tricky. For my purposes, a model should contribute towards the understanding of a phenomenon and therefore must be a more abstract version than the phenomenon itself. Adding more and more detail to a model in order to account for the complexity of a real-world phenomenon might not be the best way forward. Chirimuuta (2024, p. 5) argues that building a simulation of the human brain failed because scientists could not agree where to draw the line between what is relevant for a model of the brain and what is not. It is the hard task for modelers to find the right level of abstraction.

Chirimuuta (2024, p. 290) points out that the interaction between body and mind has been proposed to be of *"narrow-bandwidth"* (after (Haugeland, 1998, p. 220)). But what if the interaction between body and mind is of "high-bandwidth" and if it is, can a "high-bandwidth" mind-body interface be implemented in ACT-R/Phi based on connections to HumMod? In ACT-R/Phi, the interface between simulated body and mind appears to be relatively narrow. Nine HumMod variables (see Figure 3.2) are used to modulate two ACT-R parameters :ans and :egs.

The potential to broaden the interface between HumMod and ACT-R certainly exists. HumMod features over 8000 parameters (Pruett et al., 2020, p. 191f) that could be used to modulate additional ACT-R parameters based on physiology. Dancy clearly points out that the connections implemented in ACT-R/Phi are *"far from the final word in ways physiology can modulate behavior"* (Dancy, 2014, p. 69). However – as discussed in Section 2.2 – we should keep in mind what the "subsymbolic" in ACT-R represents and reflect on the possibilities available based on the role of the "subsymbolic" in ACT-R.

The trouble with implementing a "high-bandwidth" interface between body and mind is that scientists are required to abstract away from reality when trying to understand the nature of the real interface between body and mind. In a sense it requires modelers to *explicitly* ignore detailed knowledge about e.g. the brain in order to create a more general model of what the brain does. The question what the brain does can again be seen from many different perspectives and thus inform the level of detail permissible for modeling a certain functionality the brain [4].

Hudlicka (2007) touches on concrete issues related to modeling cognitive-affective re-

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[4] c.f. Chapters 9 and 10 in Chirimuuta (2024).

lations. She argues that cognitive architectures have many moving parts and *"a set of data could be accounted for by multiple mechanisms"* (p. 275). Hudlicka calls cognitive architectures with too many moving parts *underconstrained* (ibid.). In an underconstrained model, a combination of the parameters could make it *appear* as if a model was very good in e.g. fitting data from real life experiments. In reality this good fit is not there. Taatgen and Anderson (2008) discuss this same issue in relation to the fact that some model parameters can be (arbitrarily) set by modeler to make a model appear better in predicting than it actually is (p. 276). Coming from a different angle, Anderson (1991) states that any cognitive architecture could be configured in a way to produce optimal behavior (p. 22). This is a problem for ACT-R/Phi in particular as it has to account for the architectural parameters of ACT-R *and* for the additional parameters from HumMod.

Fum et al. (2007) refer to this as Bonini's paradox which aptly summarizes my thoughts: *"the risk we run in developing intricate and elaborate models is that they are no more understandable than the phenomena they are intended to explain"* (p. 137).

Adding to this, there is a possibility that we as human beings might not even be able to understand an organism of the same complexity as we are. The thoughts of Kováč (2000, p. 56)[5] appear useful at this point: Kováč suggests that any system can only be understood from *outside* of said system. This would entail that humans – using human brains – can not understand the human organism. What Kováč suggests, is to study phenomena in more simple organisms than the human one (ibid, p. 56). This would mean that we can only ever understand less complex organisms[6]. Given our human complexity and desire to understand ourselves, the question is if we will be satisfied with understanding ourselves at a level of abstraction that is necessary but at the same time also ensures that we we will never understand fully.

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[5] Kováč founded the center for cognitive biology at the Comenius University in Bratislava. We discussed this text in a class on *Cognitive Semantics and Cognitive Theories of Representation* during my exchange term in Bratislava. Find the course outline here: `https://dai.fmph.uniba.sk/~retova/CSCTR/` (accessed 2024-09-12)

[6] Efforts to understand C. elegans – a 204 neuron nematode – are well underway. Manuel Zimmer at the University of Vienna for example leads an effort to understand the Brain-Body-Environment interactions of this roundworm – including elaborate microscope setups that allow the real-time neuroimaging of the whole translucent worm.

6.3 Assesement

When I set out to investigate mind-body interfaces in ACT-R/Phi I did not know what I would expect. I knew that I would engage with ACT-R/Phi practically as well as theoretically and I knew that I wanted to relate the thoughts regarding the relation between mind and body from my master's program to the ACT-R/Phi artifact.

As I engaged more deeply with ACT-R/Phi and the literature from the cognitive sciences and discussions around the mind-body problem, I slowly started to grasp the sheer size of trying to model something like the relation between mind and body. I found myself lost (positively) in theoretical discussions around the symbiotic relationship between body and mind. I found myself drawn towards "playing" with ACT-R/Phi in order to understand how physiological values influenced parameters of the cognitive architecture. And I found myself engaged with trying to take my subjective experience in the project seriously.

When it came to discussions around the role of affect in connecting the physiological to the cognitive I found myself drawn into discussions around the relation of emotion and cognition, a question I had not spent much time on at the beginning of my thesis. I started to notice the similarities between the debates around mind and body, and cognition and emotion, and found myself wondering what affect was and what position it would take and what I could have discovered in relation to it if I had not chased one or two rabbits down holes that were ultimately not related to what I have written in this thesis.

While I engaged with literature and thoughts around circuit theories of affect I found myself wondering whether the concept of primary metaphors could be of any use when trying to relate physiological measures to affective states: An interesting line of inquiry that I also didn't have time to follow.

During my investigations I discovered approaches from robotics concerned with modeling intelligent behavior that took inspiration in physiological systems in animals and humans and I found myself wondering how these action-oriented approaches related to the cognition-oriented approach that I understand ACT-R and ACT-R/Phi to be. Another line of investigations that I lost myself in and needed to pull myself back from.

While I "lost" some time on these trails, I discovered valuable contributions that allowed me to think about the relation between mind and body in novel ways and beyond the positions I considered when writing my proposal. Other trails led me astray and sparked ideas that didn't find their place in this thesis.

From time to time it was highly challenging for me to get back to the drawing board, see what I initially set out to accomplish and pull myself back on track to finish this thesis. While I found it especially challenging to conduct this research while working 30 hours and I learned a lot about myself during this process up until the very last moment.

6.4 Did I Lay down a Path in Walking?

> *"The back-and-forth communication between cognitive science and experience that we have explored can be envisioned as a circle. The circle begins with the experience of the cognitive scientist, a human being who can conceive of a mind operating without a self. This becomes embodied in a scientific theory. Emboldened by the theory, one can discover, with a disciplined, mindful approach to experience that although there is constant struggle to maintain a self, there is no actual self in experience. The natural scientific inquisitiveness of the mind then queries, But how can there seem to be a coherent self when there is none?"*
>
> *—Francisco J. Varela, Evan Thompson and Eleanor Rosch (2016)*

From the set out of working on my thesis I have made my aim to seriously incorporate a reflective practice into my working process. I budgeted a considerable chunk of time for a work package aptly named "Reflection". As part of the workpackage I allotted time to simply *think* about my thesis. This means that I was not reading, writing or researching anything but merely sitting (often with a cup of coffee) and my thoughts surrounding the topics I was engaged with. I vividly remember the joy of simply being with my own thoughts, without outside technological interference and actively going through some problems I was engaged with. In addition to these coffee house sessions, I used a guided meditation app in which I logged a total of 228 meditation sessions totalling 41 hours since june 2021. While many of these sessions were not necessarily about the thesis itself, many were in the broader context of my work on the project. To add, I made it a priority to engage with physical exercise regularly while working on this thesis. This has led to me being in perhaps the best physical shape I have ever been.

Frankly, after engaging with a topic for some length of time on a daily basis, the lines between actively working on the thesis and not thinking about it began to blur to blur in my experience. While it was possible to discern between time on task and off task initially, as I engaged more closely (and especially more regularly) with the topics of my thesis, I was not able to tell apart the time spent on/off task. It became evident that I had the project on my mind at practically all times and I felt how something inside me shifted to become more attentive towards topics that appeared to be of interest to my thesis. Everything I perceived, I made somehow fit to what I was engaged with.

Without being able to pinpoint it, there was a point or perhaps a period of time that feels distinct from the initial work on this thesis. It is difficult for me to say what exactly happened or when exactly it happened, as many things co-occurred in the usual way where it is impossible to make out a determining factor. I would qualify this as a shift in my perception. A concept that I find fitting to describe this shift is that of becoming *thick with experience*[7]. A notion stating that there is a point when someone is engaged deeply with a topic where things became meaningful without the ability to put them into words. There is a feeling – a bodily sensation – that there is *something* there that deserves further investigation or that is somehow relevant.

I also encountered this shift in perception when reading texts related to ACT-R/Phi. One particular experience is especially salient. As I once again re-visited Dancy's dissertation I noticed something peculiar. When I encountered a mentioning of the $set-phys-vals$ function in the main text, a passage that didn't have any particular meaning to me before, suddenly became very meaningful. I trace this back to the fact that I had engaged with the ACT-R/Phi program code and because of this, I *understood* the meaning of this function more clearly. I was able to see how the function could trigger a command to be sent to HumMod to turn on a simulated IV drip as if it was physically happening. This was a particularly memorable instance where it became clear to me that my perspective has changed and I ask myself questions related to *how* things were done rather than simply trying to understand *what* was done.

Trying to reflect on this shift, I can state that the pre-requirements for the shift in perception included making regular time and place to work on this thesis. I allocated time and resources away from hobbies and time with friends and family towards work

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[7] c.f. Nelson (2003)

on the thesis. I also actively sought ought places that I could work in and established a routine of going to libraries and reading rooms that provided an environment for me where I could engage with my thesis while working 30 hour weeks.

I summarized the efforts I undertook in order to be mindful of my own experience while being engaged with the intellectual work that is writing a master's thesis. I am very grateful, that I could make this reflection an explicit part of this thesis and I fully believe that doing so was of benefit for this thesis as well as for me as a person. I feel like I was able to take seriously the scientific method and think hard about some problems surrounding the mystery of the human mind while fully embracing my subjective experience and role as a researcher. I started out work on this thesis as a cognitive science student. As I write the last lines of this thesis, I believe I have started to become a cognitive scientist.

6.5 Final Thoughts on the Bridge that is ACT-R/Phi

After spending quite some time thinking about the mind-body problem, ACT-R/Phi, and circuit theories of emotion I can not help but admire the efforts of Christopher L. Dancy. Getting somewhere requires builders of bridges that take the material they have available to build the bridge they can build at the point and space in time they are at.

In my opinion, Chris Dancy set out to build a bridge between the central nervous system and the components of the information processing system that Simon and Newell (1971, p. 157f) were not able to see in 1970. While we can and should discuss the appropriateness of HumMod, circuit theories, and ACT-R for implementing a bridge between physiology, affect, and cognition, it is undeniable that Dancy built a bridge and the fact that this bridge exists in the form of ACT-R/Phi allows everyone else to take a good look at it, to walk across it, to improve it and to take inspiration in it when building their bridge.

I believe we live in a time when the connections between the central nervous system and the information processing system are becoming ever more apparent. Taking inspiration from ongoing research in philosophy, neuroscience, affective science(s), and cognitive science(s), and using methods such as neurophenomenology, mobile physiological measurement devices, and increasingly accurate neuroimaging devices in unison, while being guided by a firm understanding that the body and brain are intimately intertwined, opens up new possibilities for exploring mind-body interfaces in the tradition of Simon and Newell. I hope I have laid out a potential foundation for (my) further inquiry into the principled modeling of the relationship between body and mind, as well as emotion and cognition.

6.6 Conclusion

In this thesis I set out to investigate mind-body interfaces in ACT-R/Phi, an extended cognitive architecture integrating a circuit theory of affect and utilizing a physiology simulation. To do so, I set the stage by providing an overview of the persons involved directly and indirectly in ACT-R/Phi to provide historical context behind the development and tie it to seminal figures in the field. Next, I analyzed the implicit assumptions underlying the decisions for implementing a mind-body interface in the cognitive architecture ACT-R, for choosing a circuit theory of affect, and for utilizing the HumMod physiology simulation. I describe the ACT-R/Phi cognitive architecture and the models that have been implemented in it. Complementing my efforts to understand ACT-R/Phi theoretically, I engaged with ACT-R/Phi from a user's perspective to gain understanding of the practical implementation of the mind-body interface. This involved analyzing the program code as well as modifying and running ACT-R/Phi models utilizing the mind-body interface implemented.

With a solid understanding of the theoretical assumptions of ACT-R/Phi and practical experience with ACT-R/Phi I engaged with discussions of the mind-body problem – with respect to cognitive architectures in general and ACT-R/Phi in particular. For this I focused on perspectives of 4E cognition on the nature of the interface between mind, brain, and body. I then discussed the relation between mind and body from the perspective of the discussion around the relation of physiology, affect, and cognition and introduced the discussion around the role of physiology and emotion for the Common Model of Cognition. Finally, I discussed the ways in which ACT-R/Phi has been received, which impact it had and research it inspired and discussed what the future of ACT-R/Phi could look like. I also discussed general issues modelers face when trying to model the mind in a computer.

This thesis contributes to the discussions around the role the body for the mind and how perspectives from 4E cognition can inform the development of cognitive architectures that attempt to take the body seriously.

Glossary

ACT-R ACT-R is a cognitive architecture that has been developed by John R. Anderson at Carnegie Mellon University in the 1990s. The cognitive architecture can be traced back to Anderson's work on human memory with the HAM model (Human Associative Memory). Later versions of ACT-R were developed by Anderson in collaboration with Christian Lebiere. ACT-R is developed in a cognitivistic mindset, i.e., with a focus on the presumed function of the human brain to realize mind and the aspects of cognition taken to be constant over time and task independent. ACT-R is modular: it consists of multiple modules that are coordinated by a central production module, which is fashioned after the basal ganglia. The modules are arranged as spokes of a wheel around a hub: the central production module. ACT-R is considered a hybrid architecture since it combines symbolic properties as well as numerical parameters/meta parameters. These numeric parameters are often referred to as subsymbolic parameters. "Subsymbolic" parameters in ACT-R are not to be confused with connectionist networks (neural networks) that are often referred to as subsymbolic. The subsymbolic parameters in ACT-R represents numerical values/parameters that are attached to symbolic representations in ACT-R. These subsymbolic parameters are important for determining which symbolic representations are selected for operations in ACT-R. The "subsymbolic" parameters not accessible to agents.

ACT-R/Phi ACT-R/Phi (also: ACT-R/Φ) is the name for a modified version of the ACT-R cognitive architecture resulting from Christopher Dancy's effort to model the relation between cognition, affect and physiology. Dancy extended ACT-R with modules based on the primary affect theory that implements gateways between a selection of HumMod's physiological variables and affective states (Step 1, according to primary-process affect theory) and affective states and core modules of ACT-R

(Step 2). The first version was presented in Dancy's PhD thesis completed in 2014 at The Pennsylvania State University.

Cognitive Architecture Cognitive Architectures provide consolidated externalized forms of knowledge as conceptual and programming frameworks for the computational modeling and evaluation of the operation of cognitive processes involved in specific higher-level activities, such as driving a car. Such architectures are informed and constrained by results from research spanning across all of cognitive science, including psychology, psycho-physics, neuroscience and biology, as well as philosophical inquiries on the nature of the mind.

Common Model of Cognition The Common Model of Cognition (formerly known as the "Standard Model of the Mind") is an effort to create a blueprint of the requirements for a fully fledged Cognitive Architecture. The efforts are to create a minimum consensus across active cognitive modelers. The Common Model of Cognition is heavily influenced by the work on ACT-R and SOAR, arguably the two biggest cognitive architectures.

computational theory of mind a theory claiming that the mind is a computing device implemented in the nervous system but in particular in the brain; closely associated with functionalism

Dualism claims that the body and the mind are made up from different types of matter

Functionalism claims that the mind does arise from the functions of the body, not from the mere physical makeup of it; enables multiple realizability; functionalism is compatible with physicalism

HumMod HumMod is a large multiscale model of human physiology that models the relation between multiple systems inside the human body including that of organs, the circulatory system, and the endocrine system. While not complete and certainly a topic of its own, it is – to my understanding – still the most complete and detailed implementation of knowledge in human physiology. HumMod is available as a computer program that allows for the simulation of a "body" across time. HumMod includes the option to manipulate the simulation by e.g. influencing the breathing rate (and thus Heart Rate Variability (HRV)) or by administering a infusion.

Monism claims that the body and the mind are made up from the same type of matter

Multiple realizability claims that the mind can be realized in different ways; based on functionalism

Physicalism claims that the matter that everything is made up from is physical matter; physicalism is a type of monism

primary affective systems – primary process systems Used interchangeably to refer to the Primary Process Systems developed by Jaak Panksepp, Lucy Biven, and colleagues.

Standard Model of the Mind see: Common Model of Cognition

Substrate independence claims that the mind can be realized in different substrates, i.e. in silico

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Appendix A

ACT-R/Phi Quick Start Guide

In this Appendix I will lay out the hardware and software I used to work with ACT-R/Phi and provide instructions on how to get started with ACT-R/Phi.

A.1 Hardware

- Lenovo ThinkPad X13
- AMD Ryzen 3 PRO 5450U
- 16 GB RAM
- 500 GB SSD

A.2 Software

- Windows 10 Enterprise (Version 10.0.19045 Build 19045)
  - Important: ensure that the system wide setting for the decimal symbol is set to the U.S. standard '.' (dot): Settings » Region » Additional Settings. This is required, because the HumMod ModelSolver will crash otherwise.
- GNU Emacs 29.1
- SLIME 2.28
- Clozure CL (CCL)[1] 1.12.2 windowsx86

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[1] I attempted to run ACT-R/Phi using Portacle - A Portable Common Lisp Development Environment. Portacle uses SBCL (Steel Bank Common Lisp) which unfortunately did not cooperate with ACT-R/Phi because of file path issues.

- ACT-R/Phi is available at `https://git.psu.edu/thicc-lab/act-r_phi` (accessed 2024-09-12).
    - ACT-R/Phi consists of:
        - ACT-R 7.13.5$- < 2888 : 2019 - 07 - 02 >$
        - /user-loads folder containing the ACT-R/Phi modules:
            - Physiology_thread.lisp
            - Affective-Associations.lisp
            - FEAR.lisp
            - SEEK.lisp
        - /phys-test-models folder containing the ACT-R/Phi test model:
            - Test-Model.lisp
    - HumMod consists of the following files and folders:
        - Control
        - Data
        - Docs
        - Structure
        - HumMod.des
        - HumMod.exe (Version: 2.0.38)
        - ModelSolver.exe (Version: 1.0.16, Build: 2022-1-2)
        - ModelSolver.ini

A.2.1 Setting up Lisp

- Download and Install Emacs (I'm using 29.1): `http://mirror.easyname.at/gnu/emacs/windows/emacs-29/` choose the emacs-29.1-installer.exe

- Setup Melpa (Milkypostman's Emacs Lisp Package Archive, a repository for Lisp packages) following the instructions here: `https://melpa.org/#/getting-started`
    - Create a init.el file in the appropriate folder: e.g. `C:\Users\David\AppData\Roaming\emacs.d` with the initial content:

Listing A.1: Content of init.el file to set up Melpa

```
(require 'package)
(add-to-list 'package-archives '("melpa" . "https://melpa.org/packages/") t)
(package-initialize)
```

- Alt - x package-refresh-contents ↲ [2]
- Install Slime: Alt - x package-install ↲ slime ↲
- Close Emacs and download the CCL (Common Clozure Lisp) Executable: `https://github.com/Clozure/ccl/releases/tag/v1.12.2`
- `ccl-1.12.2-windowsx86.zip` in my case
- unpack the .zip and add a line to your `init.el` file pointing to `wx86cl.exe`:

Listing A.2: Add line to init.el file

```
(setq inferior-lisp-program "C:/Users/David/ccl-1.12.2-windowsx86/ccl/wx86cl.exe")
```

- Start Emacs and Alt-x slime ↲ to start slime with CCL

A.3 Starting ACT-R/Phi

Obtain a copy of ACT-R/Phi for example from the THiCC Lab GitLab `https://git.psu.edu/thicc-lab/act-r_phi` (last downloaded 2023-10-19)

1. Load ACT-R in SLIME by entering and executing the following command (adjusting the directory path as appropriate):

```
(load "C:/Users/davidc91/ucloud/Masterthesis_CserjanD/97_ACT-R-PHI/act-r_phi-main/load-act-r.lisp")
```

2. Start the environment: `(run-environment)`
3. Load a model using the environment GUI: for example the `phys-test-models` ▸ `Test-Model.lisp`

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[2] M-x package-refresh-contents RET (M(eta) M(eta)=-x is Alt-x in Windows. RET is the Return Key)

   - You can utilize the Stepper functionality to advance models step by step!

4. Run ACT-R/Phi models in SLIME:
   - `(run-test-model10)`
   - `(run-graded-stress1)`
   - `(run-graded-stress2)`

   (a) Note: When running ACT-R/Phi models, HumMod starts automatically. Depending on your screen resolution, the HumMod window might not be on screen. Fix this by adjusting the content of the `HumMod.INI` file located in the user-loads folder (setting the values in top and left to 1 will open HumMod in the top left corner of the screen)

A.4 Monitoring ACT-R/Phi

When you run an ACT-R/Phi model, HumMod will be loaded by the physio module:

0.005 PHYSIO Schedule all physio module-based setup events

This will:

- Load the HumMod Physiology Simulation Model Solver;
- Parse the initial conditions of the Model Solver: This way, the Starting point of the physiology simulation is set[3];
- When Parsing is successful, a SolverOut{PipeID} File is created. This is the file. which ACT-R/Phi uses to read from HumMod;
- A SolverIn{PipeID} file is used to feed changes into HumMod;

One low level way to monitor ACT-R/Phi is to advance an ACT-R/Phi model using the stepper in the ACT-R GUI[4] and to monitor the files (SolverIn and SolverOut) created by the ACT-R/Phi modules destined for the HumMod Model Solver.

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[3] Starting conditions can be created by running the HumMod physiology simulation on its own, configuring it to ones liking, and exporting it in the form of an .ICS (=InitialConditionS) file and loading it in the ACT-R model code.

[4] Refer to the helpful ACT-R tutorials to learn about the stepper, which allows you to advance a model one ACT-R operation after the other.

A.5 Recording ACT-R/Phi Data

If ACT-R/Phi is set to record data, it stores physiology and some ACT-R system variables in the home location of your Lisp interpreter. To enable recording, schedule a periodic event, for example:

Listing A.3: Scheduled periodic event that records ACT-R/Phi variable values.

```
(schedule-periodic-event 1 'test-record-arousal :module :physio :
    output nil :initial-delay 2)
```

In order to change the default location where recordings are stored, the working directory of CCL needs to be changed. To change the working directory of CCL, use the *ccl* :: *cwd* command[5]. For example:

```
(ccl::cwd "c:/Users/davidc91/")
```

Taking the example above, ACT-R/Phi writes the following files to the `c:`‣`Users`‣`davidc91` folder: *arous − ans − log.txt* is written directly into the folder.

- *arous − ans − log.txt*
  - time.s
  - Arousal
  - ans

In addition, a *Phys − data* folder is created, containing additional files: *CEC − Arous.txt*, *CORT − RAW.txt*, *CRH − RAW.txt*, *EPI − RAW.txt*, and *Homeostatic − Arousal.txt*. These files contain the following HumMod variable and ACT-R parameter values:

- *CEC − Arous.txt*
  - time.s
  - time.ms
  - Homeostatic-Arousal-Factor
  - f(Cortisol)
  - g(Epinephrine)
  - h(CRH)

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[5] Make sure to select a folder to which you have full read and write access.

  - Arousal
  - ans
  - egs
  - ut

- *CORT – RAW.txt*
  - Time (ms)
  - Cortisol
  - Cortisol (baseline)
  - Cortisol (gain/loss ratio)
  - Cortisol (gain/loss ratio-baseline)

- *CRH – RAW.txt*
  - Time (ms)
  - CRH Stress Effect
  - CRH
  - Cortisol (Baseline)

- *EPI – RAW.txt*
  - Time (ms)
  - Epinephrine
  - Epinephrine (Baseline)

- *Homeostatic – Arousal.txt*
  - Homeostatic-Arousal
  - Time since last sleep

A.6 Issues and Solutions

Issue ACT-R/Phi attempts to save logs in the current working directory in CCL. In case of insufficient writing rights, ACT-R/Phi models will crash when trying to record values.

Solution Change the working directory of CCL to a directory, where the current user has writing rights.

Solution Run Emacs as Administrator