Increasing Realism of Human Agents by Modeling Individual Differences: Methodology, Architecture, and Testbed

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Abstract

A key challenge in creating simulated human agents is to produce sufficiently realistic behavior. A critical component of such realism is the range of variations in behaviors exhibited by humans. These variations are due to a variety of factors, including varying levels of intelligence and skill, differences in cognitive and decision making styles, personality differences, and different affective states: collectively termed individual differences. In this paper we describe an approach for increasing the realism of simulated human agents by explicitly modeling these individual differences. The core component of this approach is a generic methodology for modeling individual differences within symbolic cognitive architectures, via parametric manipulations of the architectural structures and processes. Individual differences profiles are first translated into specific architecture parameters, which then bias the architecture output in corresponding directions, causing variations in performance. The architecture is embedded within a modeling and analysis testbed environment, which supports the simulation of multiple agent interactions within the task simulation; modeling of a variety of agent types by specifying their distinct individual differences profiles; and modeling and analysis of alternative mappings of distinct individual differences onto the cognitive architecture parameters. Prototype versions of the cognitive architecture and testbed have been implemented and evaluated in the context of a military simulation training scenario, representing the interaction of a number of commanders in the context of a specific mission. The simulated mission demonstrated distinct differences in individual commander behavior, as a function of their individual profile, and consequent significant differences in the final mission outcome. The testbed environment was effective in facilitating the rapid selection of alternative individual differences profiles and observation of resulting individual behavior variations and subsequent mission outcome. These preliminary results indicate the ability of the modeling methodology to effectively represent individual differences, and the ability of the testbed to support flexible exploration in the broad research area of individual differences modeling.

Introduction

A key challenge in creating simulated agents is to produce sufficiently realistic behavior. A critical component of such realism is the range of variations in behaviors exhibited by humans. Whether these be 'leaps of genius', surprising reactions, specific biases, suboptimal behaviors, or simply errors, these inconsistencies and idiosyncracies are quintessential human qualities. These variations are due to a variety of factors, including varying levels of intelligence and skill, differences in cognitive and decision making styles, personality differences, and differences in specific affective states and moods. Collectively, these factors are termed *individual differences*.

A number of questions must be addressed in representing these factors in human simulation models. These include the following:

- How stable are these influences within an individual; across individuals; across tasks?
- Which specific cognitive, perceptual, or motor processes are influenced by these factors? What are the exact mechanisms of these influences?
- Which specific individual differences should be represented in a particular agent? At what level of resolution should these representations exist?

To answer these questions one would ideally turn to psychological literature for empirical data about the influences of individual differences on behavior, and to cognitive psychology for details regarding the mechanisms of these processes. However, the state of the art in these disciplines does not yet permit this approach; existing empirical data are sparse and theories of specific cognitive and perceptual mechanisms often do not provide sufficient level of detail, or consistency.

This state of affairs therefore necessitates an experimental approach to modeling individual differences: one that supports rapid definition of distinct individual difference profiles within a specific agent model, and a flexible exploration of alternative mappings of the individual differences factors onto the cognitive architecture structures and processes, to accommodate rapid integration of newly emerging empirical data and theories.

In this paper we describe a such an approach and its implementation: the Methodology for Analysis and Modeling of Individual Differences (MAMID).

Our approach consists of three components:

- a *generic methodology* for modeling individual differences within symbolic cognitive architectures, via parametric manipulations of the architectural structures and processes;
- a *parameterized cognitive architecture*, providing a sufficiently rich representational and processing environment for modeling the varied effects of these differences at multiple points of processing;

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- an *exploratory testbed environment* supporting the interaction of multiple agents within the task simulation; modeling of a variety of agent types by specifying their distinct individual differences profiles; and modeling and analysis of alternative mappings of distinct individual differences onto the cognitive architecture parameters.

Prototype versions of the cognitive architecture and testbed have been implemented and evaluated in the context of a military simulation training scenario, representing the interaction of a number of commanders in the context of a specific mission (Hudlicka & Billingsley, 1999). Each unit commander is represented by an instance of the cognitive architecture, whose behavior is controlled by the individual differences parameters representing that commander's individual profile. The prototype enabled the simulation of a variety of agent types (e.g., high / low anxious, high / low aggressive, high / low obsessive, etc.). The simulated mission demonstrated distinct differences in individual commander behavior, as a function of their affective / personality profile, and consequent differences in the final mission outcome.

This paper is organized as follows. We first outline categories of individual differences factors and provide a brief summary of their influence on cognition, perception, and behavior. We then describe a generic method for modeling the effects of individual differences within cognitive architecture, an experimental parameterized cognitive architecture demonstrating this modeling method, and the associated testbed and simulation environment within which this architecture is embedded. We briefly summarize the implementation status. The paper concludes with a summary, conclusions, and discussion of future work.

Effects of Individual Differences Factors on Behavior

The past decade has witnessed a renewed interest in the exploration of the effects of individual differences on performance (Revelle, 1995). However, no single psychological or neuroscience theory that provides *the* definitive, orthogonal set of cognitive, affective, personality, and individual differences. Rather, each subdiscipline within the psychological sciences defines its own set of factors, as a function of a particular theoretical perspective, methodologies, and specific application of interest. Thus personality theorists in academic psychology speak of "Big 5" personality traits (extraversion, stability, openness, agreeableness, and conscientiousness) (Costa & McCrae, 1992) and "Giant 3" (approach, avoidance, fight / flight) personality traits (Eysenck, 1991), emotion researchers speak of basic emotions (the exact number varies but generally joy, sadness, fear, anger, surprise, and disgust are considered basic). Cognitive psychologists speak of general cognitive abilities (e.g., attention and working memory capacity, speed, and accuracy), cognitive biases (e.g., availability, consistency, confirmation bias, order effects, etc.) (Tversky & Kahneman, 1981). and specific skills and cognitive styles, clinicians speak of distinct personality styles (e.g., avoidant, passive-aggressive, narcissistic, etc.), and political psychologists consider high-level traits relevant to leadership and interpersonal decision-making style (e.g., authoritarianism, dogmatism, ease of persuasion, locus of control, need for power, need for affiliation, etc.) (Shaw and Post, 1999). Furthermore, these factors are defined at varying levels of abstraction (e.g., negative emotionality vs. anxiety-prone vs. suffering from agoraphobia), and varying levels of detail with respect to their specific mechanisms (e.g., high intelligence vs. high attentional speed and working memory capacity).

Not all of the identified factors have been studied extensively, and the available data do not always provide unequivocal results. Nevertheless, certain regularities emerge from the existing evidence regarding the influences of some of these factors on perceptual, cognitive, decision-making, and motor mechanisms mediating behavior (LeDoux, 1989; Williams et al., 1997; Mineka and Sutton, 1992; MacLeod and Hagan, 1992). For example, fear and anxiety influence attentional focusing processes and perceptual categorization processes to enhance the detection of threatening stimuli; increased levels of obsessiveness correlate with increased checking behaviors and lead to delays in decision selection (Broadbent et al., 1986); mood influences type of material recalled from memory (Blaney, 1986); low level of emotional stability predisposes towards anxiety; etc. Empirical evidence also suggests that the extent of influence varies with context; that is, by the individual and the task. The exact manifestations of these factors also vary within specific individual based on other contextual factors (e.g., skill level, general cognitive abilities, individual history, prior experience with the task, current affective state, current interpersonal environment, etc.). Given the complexity of the phenomenon, how then do we select the specific factors to include in a particular model / agent simulation?

We have identified a number of criteria for this selection process: 1) availability of empirical evidence demonstrating the existence of the individual differences factor and an associated performance effect; 2) sufficient effect size to warrant the inclusion of the factor within the model; 3) sufficient robustness of existing empirical findings to allow generalizability to the context of interest (e.g., military simulation, medical decision making, gaming); 4) relevance of particular factor within the context of interest (i.e., does the influence of the particular factor emerge within the task of interest or does the task environment provide performance constraints

which limit the manifestations of individual differences); and 5) theoretical and empirical basis for mapping the factor's influence onto a cognitive architecture. Again, given the lack of definitive empirical data, a critical component of the final selection process is an extensive cognitive task analysis and knowledge elicitation with a subject matter expert.

For the initial prototype implementation, we divided the individual differences factors into three broad categories: cognitive, affective, and personality. Several factors from each category were then selected to provide adequate complexity capable of validating the modeling approach and the cognitive architecture, evaluating the testbed functionality, and providing interesting and meaningful variations in performance. These factors are briefly described below.

Cognitive

- Skill level was selected because it determines the knowledge structure and contents mediating task performance (e.g., perceptual categories for situation assessment, situation to action mapping, action repertoire).
- General intelligence was selected because defines baseline limiting capabilities of the fundamental processes within the perceptual – cognitive apparatus (e.g., attention and working memory accuracy and capacity).
- Individual history factors were selected as critical components in defining specific affective connotations for particular situations (e.g., success or failure associated with a specific recent situation influences level of anxiety in a similar situation, etc.).

Affective

- Anxiety was selected as the primary affective factor because of its relevance to the task (military simulation), and the extensive empirical data documenting consistent influence on attention and perception (e.g., narrowing of attention, biasing towards threats).

Personality

- Emotional stability was selected as a factor influencing anxiety manifestation and rate of decay.
- Aggressiveness was selected as a critical personality factor relevant to the simulation task domain.
- Obsessiveness, a state resulting from a combination of high anxiety and high conscientiousness, was selected as an important factor influencing speed and accuracy of decision-making.

Methodology for Modeling Individual Differences in Agent Architectures

The core component of our approach is a *generic methodology* for modeling individual differences within symbolic cognitive architectures, via parametric manipulations of the architectural processes and structures. A key objective of the methodology is to provide flexibility regarding the *types of factors* selected for inclusion in a model, the *nature of their influence* on cognitive, perceptual, and decision-making processing, and the *degree of this influence*. Such flexibility then supports an experimental approach to model development, by providing the following features: 1) flexible selection of parameter combinations to represent in the model (i.e., distinct individual profiles); 2) rapid incorporation of emerging empirical data; 3) varying the level of representational abstraction of a particular factor, depending on the needs of the particular application; 4) modification of the specific effects of a particular factor depending on the theoretical perspective represented and knowledge of the underlying mechanisms.

The modeling approach achieves this flexibility through a parameterization of individual cognitive architecture processes and structures (Hudlicka, 1997; Pew & Mavor, 1998). The distinct individual differences factors are then mapped onto these cognitive architecture parameters. Figure 1 illustrates this approach. The effects of individual differences factors can be modeled in two primary ways: 1) by manipulating the model *processing* parameters (e.g., attention capacity & accuracy), to reflect a particular cognitive and decision making style, or a particular affective personality factor (e.g., susceptibility to anxiety), thereby biasing the model behavior in a particular direction (e.g., detection of threatening cues in the environment); and 2) by manipulating the model *content* (e.g., structure and contents of rules, semantic nets, belief nets, etc.) to reflect the desired characteristics (e.g., varying levels of skill and training, stable perceptual biases, decision making preferences, different individual histories, etc.).

The first step for both the modeling and the adaptation research goals was to review existing empirical psychological literature to identify key affective and personality factors influencing behavior. The *affective states* studied most extensively include anxiety, positive and negative mood, and anger. The effects of these states on behavior range from influences on distinct information processes within the cognitive architecture (e.g., attention and working memory capacity, accuracy, and speed; memory recall biases), through autonomic nervous system manifestations (e.g., heart rate, GSR), to visible behavior (e.g., facial expressions, approach vs. avoidance tendencies, aggressive behavior, etc.) (LeDoux, 1898; Williams et al., 1997; Mineka and Sutton, 1992; MacLeod and Hagan, 1992). A wide variety of *personality traits* have been studied, ranging from general, abstract behavioral tendencies (e.g., "Big 5" (Extraversion, Emotional Stability, Agreeableness, Openness, Conscientiousness), and "Giant 3" (Approach behaviors, Inhibition behaviors, Aggressiveness) personality factors), through psychodynamic / clinical personality formulations (e.g., narcissistic, passive-aggressive, avoidant, etc.), to characteristics relevant for particular type of interaction (e.g., style of leadership, preferred style of social interaction, decision making, etc.) (Revelle,

1995). Our initial primary focus in both the modeling and the adaptation research areas was on anxiety, aggressiveness, and obsessiveness.

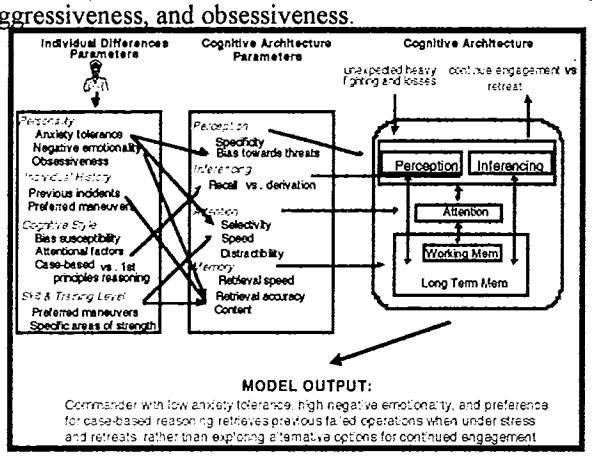

Figure 1: Summary of Proposed Methodology for Representing Individual Differences in Human Performance Models

Parameterized Cognitive Architecture

The *parameterized cognitive architecture* implements the modeling methodology described above, by providing a rich representational and processing environment for modeling the varied effects of the individual differences factors. Several objectives motivated the design of the MAMID experimental cognitive architecture: 1) consistency with existing theories and empirical data; 2) ability to generate the desired task performance; 3) ability to encode the influence of the selected individual differences factors via parameterized processing, as required to implement the modeling methodology discussed in section 3 above; 4) ability to explicitly model distinct stages of processing, to enable the encoding of parallel effects of a particular factor on distinct components of the perceptual – cognitive apparatus (e.g., anxiety effects on attention AND perception, etc.).

These considerations led to the design of a symbolic, integrated cognitive architecture consisting of five modules: *sensory pre-processing*, providing the external cues representing the current state of the world; *attention*, filtering the incoming cues and selecting a subset for further processing; *situation assessment*, mediating information integration by combining individual cues into an overall situation assessment; *decision selection*, selecting an appropriate action based on the current situation assessment; and *procedure execution / monitor*, closing the loop by integrating feedback from actions from the environment (see figure 2). The individual modules are assumed to have access to the memory structures containing the domain and problem-solving knowledge (long term memory (LTM) and working memory (WM)), and consisting of rules (decision selection module) and belief nets (situation assessment module). The architecture modules thus use multiple representational formalisms to implement a variety of inferencing types.

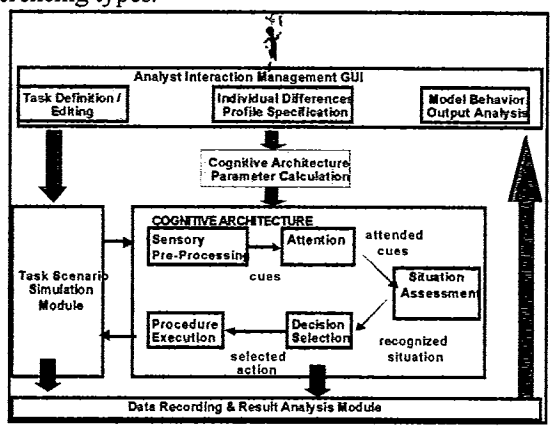

Figure 2: MAMID Cognitive Architecture and Associated testbed Environment

Processing within the MAMID architecture is determined in part by the various parameters controlling their individual module processing, and in part by the structure and contents of the memory structures (e.g., nature and content of rule-bases, topology of belief nets).

The architecture and module processing details are described in detail elsewhere (Hudlicka and Billingsley, 1999). Here we briefly describe one of the architecture modules, Situation Assessment, to illustrate the general approach. The situation assessment module is implemented in terms of belief nets (Pearl, 1986), which map the incoming cues, selected by the attention module, onto high-level situations, using the belief net probabilistic inferencing engine. Incoming cues, representing low-level features and events (e.g., enemy unit approaching), are combined into intermediate results (e.g., enemy unit within weapons range), and finally derive the overall situation types (e.g., unit under attack). A number of factors influence the situation assessment process, including the current situation, expectations, and goals, current affective state, variety of cognitive individual differences factors (general, stylistic, and specific skill), and personality traits. The specific skill and individual history factors determine the overall network contents, topology, and conditional probabilities linking the individual nodes. The general cognitive capacity factors determine the processing speed and accuracy. Working memory capacity is reflected in the number of incoming cues that can be processed by the network. Anxiety is represented by a distinct node within the belief net, and linked to all nodes representing propositions (i.e., specific perceptions) influenced by anxiety. This explicit representation thus allows the representation of the biasing effects of anxiety on perceptual categorization; that is, the increased likelihood of assuming the existence of a more threatening situation. Figure 3 shows an example of a belief net deriving the probability of attack.

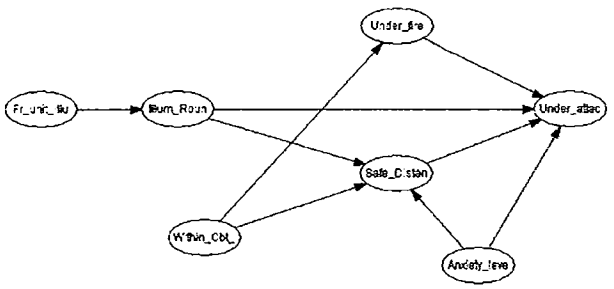

Figure 3: Example of a Situation Assessment Belief Net, Showing an Explicit Representation of the Anxiety Level Future Work

Distinct agent types are modeled by defining an *individual profile*, consisting of specific values for the individual differences factors (e.g., an anxiety-prone, intelligent, but novice commander would have high general cognitive abilities, low skill level, low emotional stability, and high anxiety; a obsessiveness-prone, highly skilled commander would have high skill level, high conscientiousness level, high anxiety level, etc.). These profiles are then translated into specific cognitive architecture parameter values and structural memory (knowledge base) modifications, which determine the exact model behavior. This cognitive architecture is loosely based on the Charles River Analytics SAMPLE architecture (Zacharias et al., 1996), which was augmented with additional structures and processes, as necessary, to enable the modeling of the selected individual affective and personality.

Modeling and Analysis Testbed Environment

The MAMID *testbed* provides an experimental environment supporting the modeling of a variety of agent types in terms of the architecture described above, and their interaction within the task simulation environment. Specifically, the MAMID testbed supports the definition of specific task scripts, and individual commander profiles in terms of distinct individual differences factors, and the simulation of the resulting commander behavior, to demonstrate both the modeling methodology and the effects of the individual commander's behaviors on the overall mission outcome. A testbed approach is necessitated in part by the fact that existing empirical evidence does not always support the definitive determination of the factors influencing particular task performance, and in part because the state-of-the-art in empirical psychological literature, cognitive science, and AI, does not yet allow the specification of *the* definitive set of mappings among individual differences factors and cognitive architecture parameters.

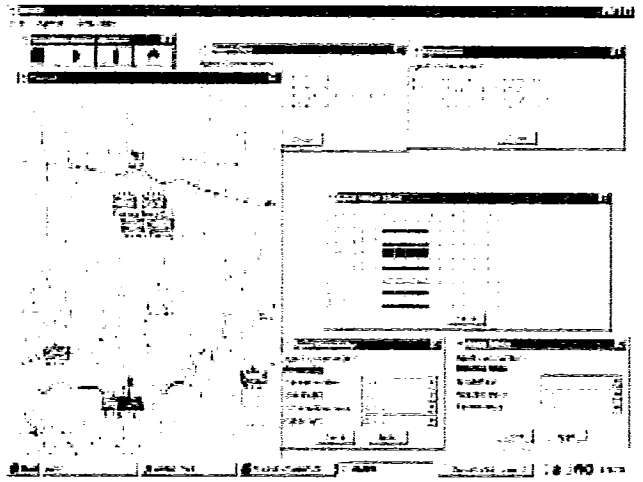

Figure 4: MAMID Testbed GUI Showing Simulation Output (left) and a Variety of Monitoring Displays (right)

The MAMID testbed consists of the following components (refer to figure 2): *the Analyst Interaction Management* module, supporting scenario selection and definition, specification of the simulated commander's individual differences profiles used during a simulation run, specification of MAMID run-time parameters to control system performance monitoring, facilitating the user / analyst control of the simulation, and displaying an animated version of the scenario (i.e., a military simulation situation sketch), where the visible effects of distinct agent profiles can be observed as the simulated mission unfolds (e.g., aggressive commander, anxious commander, etc.); a *Cognitive Architecture Parameter Calculation* module, mapping the individual differences factors onto the cognitive architecture parameters controlling processing; the *parameterized Cognitive Architecture*, implementing the distinct modules discussed above; and a *Task Scenario Simulation module*, implementing the simulation functionality required for the demonstration scenario.

Figure 4 illustrates a specific configuration of the MAMID testbed Analyst GUI, showing the simulation output (map with overlaid military unit symbols representing a particular mission situation) and a variety of system monitoring windows and individual profile specification displays.

MAMID Implementation and Status

To demonstrate and evaluate the MAMID modeling methodology, we implemented the cognitive architecture and testbed described above, and evaluated its performance in the context of a simulated military engagement. The behavior of each unit commander was modeled by an instantiation of the MAMID cognitive architecture, whose exact behavior was determined by the individual differences profile associated with that commander. The different individual profiles specified

distinct commander personalities and backgrounds, resulting in differences in information processing and observable behavior. A variety of distinct profiles were specified (e.g., high / low anxious, high / low aggressive, high / low obsessive, etc.), resulting in observable differences in the overall mission development and outcome (see Hudlicka and Billingsley (1999) for a more detailed discussion).

Summary, Conclusions, and Future Work

Summary We described a research approach aimed at producing more realistic behaviors in simulated human agents. The approach consists of three components: a generic methodology for modeling the effects of a variety of individual differences factors on performance, by manipulating the processing and structural parameters of a symbolic cognitive architecture; a parameterized cognitive architecture, which controls the agent behavior; and an experimental testbed. The high degree of architecture parameterization allows the flexible exploration of the effects of a variety of distinct individual differences profiles on performance, thereby enabling the modeling of a variety of agent types, and their interaction, within the testbed environment. A prototype cognitive architecture was implemented within an integrated simulation and analysis testbed environment (Windows/ NT; Java; JESS, JavaBayes). The initial domain was a military simulation training scenario, representing the interaction of a number of commanders in the context of a specific force-on-force mission. Each commander's behavior was controlled by an instance of the cognitive architecture, whose behavior in turn was determined by the individual differences profile representing the commander's cognitive, affective, and personality individual differences factors.

Conclusions The simulated mission demonstrated distinct differences in individual commander behavior, as a function of their individual profile, and consequent significant differences in the final mission outcome. The testbed environment was effective in facilitating the rapid selection of alternative individual differences profiles and observation of resulting individual behavior variations and subsequent mission outcome. These preliminary results indicate the ability of the modeling methodology to effectively represent individual differences, and the ability of the testbed to support flexible exploration in the broad research area of individual differences modeling. Together, they indicate a general feasibility of the modeling approach. Although the initial prototype was developed within the military domain, the modeling methodology and architecture are applicable across a broad variety of non-military application areas, as outlined below. In addition to enabling the modeling of more realistic behavior in simulated human agents, the methodology and testbed environment also provide a research tool for investigating broader issues in computational cognitive modeling, by supporting the rapid testing of theoretical hypotheses regarding the exact mechanisms of influence of a variety of individual differences factors on perceptual and cognitive processing.

Future Work Future work falls into several categories of effort: 1) Expansion of the set of individual differences factors modeled (e.g., broader set of cognitive styles, emotions, and personality traits); 2) Enhancements of the cognitive architecture to include learning and more complex planning, as well as modifications in the overall structure of the architecture (e.g., non-linear, opportunistic processing); 3) Enhancements of the testbed functionalities to support more extensive architecture parameter modifications; 4) Application of the approach in different domains (e.g., virtual reality training and treatment environments in mental health; team training environments; and interactive education and gaming environments).

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