SCHOOL OF INFORMATION SCIENCES AND TECHNOLOGY
THE PENNSYLVANIA STATE UNIVERSITY

Defining Testable Theories of Pre-task Appraisal Stress

Frank E. Ritter, Andrew L. Reifers, and Michael J. Schoelles

frank.ritter@psu.edu

Technical Report No. ACS 2005-2

30 August 2005

Applied Cognitive Science Lab
School of Information Sciences & Technology
University Park, PA 16802
acs.ist.psu.edu

Phone +1 (814) 865-4455 Fax +1 (814) 865-6426

Defining Testable Theories of Pre-task Appraisal Stress

Frank E. Ritter and Andrew L. Reifers

frank.ritter@psu.edu, areifers@ist.psu.edu
Applied Cognitive Science Lab
College of Information Sciences & Technology
University Park, PA 16802
acs.ist.psu.edu
Phone +1 (814) 865-4455 Fax +1 (814) 865-6426

Michael J. Schoelles

schoem@rpi.edu
Department of Cognitive Science
Rensselaer Polytechnic Institute

Technical Report No. ACS 2005-2

30 August 2005

Abstract

We describe a range of theories of how cognition is influenced by stress. We use a cognitive architecture, ACT-R, to represent these theories formally. The theories make suggestions for developing cognitive architectures, in that they nearly all of them require that time-on-task influence performance, and at least one suggests that workload and strategies are monitored to access and cope with stress. By examining the theories as a whole, we can also see that they are incomplete in that individually and as a group they do not make predictions that are consistent with data. For example, many of them do not predict that repeated serial subtraction (part of the Trier Social Stressor Task) will be affected by stress. We also see how the stress theories and the mechanisms that give rise to them can be tested.

Acknowledgements

Susan Chipman has provided several types of support for this work. Wayne Gray, Mike McNeese, Karen Quigley, and Roman Belavkin have helped our thinking in this area. The ACT-R community provides a background for this work. This project was supported by the US Office of Naval Research, award number N000140310248.

A much revised version of this report will appear as: Ritter, F. E., Reifers, A. L., Klein, L. C., & Schoelles, M. (accepted January 2006). Lessons from defining theories of stress. *Integrated Models of Cognitive Systems (IMoCS)*, Wayne Gray (ed.). New York, NY: Oxford University Press.

Table of Contents

1. Introduction

The approach of classifying architectural mechanisms into Type 1 (central control) and Type 2 (local control) introduced by this book is an interesting and useful approach. We use this approach to examine how a range of cognitive theories of stress would be represented and implemented in a cognitive architecture.

Including these theories (overlaying these theories) into cognitive architectures offers several advantages. We will be able to construct models that make pre-task appraisal and stress theories more precise. Until now these theories have typically only been verbally stated. We will be able to provide more realistic opponents in competitive environments. We also will learn where cognitive architectures can be improved, as most architectures have not been developed with these theories of stress in mind.

The pre-task appraisal and stress theories are not all complete. By implementing them in one architecture, we will come closer to an integrated theory of how stress influences cognition. As a result of this review we will also be able to suggest some new aspects to cognitive mechanisms (such as the effects of time and strategy), and find other suggestions for where to improve cognitive architectures.

Before introducing the theories for implementation as overlays to ACT-R, we briefly review task appraisal, cognitive architectures, and what we mean by overlays. We also review the most relevant aspects of ACT-R as a summary for those who do not know it.

2. Task appraisal, architectures, and overlays

We start this review by describing a bit about stress and pre-task appraisal, cognitive architectures, and overlays.

2.1 Pre-task appraisal and stress

Many types of stressors influence how cognition is affected by outside effects. There are now several reviews and resources that summarize moderators of cognition (Pew & Mavor, 1998; Silverman, 2004). Moderators of cognition can range from external sources such as heat and vibration to internally generated changes based on what is processed (Ritter, 1993).

Pre-task appraisal is one kind of stress that influences performance. It is based on an appraisal before doing a task of how difficult the task will be, and how well people think they will be able to cope with the task's demands. These appraisals are typically classified into "threatening" or "challenging" appraisals. Threatening tasks are those where the coping demands are not great enough for the task, and challenging indicates that the resources are great enough to meet the task demands.

Challenging appraisals give rise to better energy mobilazation, and better performance in general. Threatening appraisals give rise to poorer energy mobilization and poorer performance. This result has been shown in a variety of studies. In particular, performance on repeated serial subtraction has been used to study this effect (e.g., Quigley, Feldman Barrett, & Weinstein, 2002; Tomaka, Blascovich, Kelsey, & Leitten, 1993). In these studies, where the appraisal is manipulated and knowledge held constant, threatening appraisals leads to about a 25% slower performance, but with the same accuracy (Tomaka et al., 1993).

Lazarus and Folkman (1984) and Hancock and Szalma (2003) note that coping influences the task or that the task is a type of stress itself. Most of the theories we will examine make simpler assumptions, that the effects of stress can be represented with a static approach of modeling unstressed (challenged, perhaps) and stressed (threatened). In many theories and most of our implementations the effects of stress are assumed to be there or to not be there. This is probably simplistic, but will be a helpful assumption for starting this work.

2.2 Cognitive Architectures

Cognitive architectures are an attempt to represent the mechanisms of cognition that do not change across tasks. Typically, cognitive architectures include a long-term procedural and declarative memory, a central processor and some working memory for that processor, and perceptual and motor components. Newell (1990) provides a useful overview of this approach.

Gray (Chapter 3) references two types of control mechanisms in cognitive architectures. Type 1 theories are those that have central control. A central executive processor represents this type of control. Type 2 theories speak to peripheral processors and distributed control. It is likely that the human mind has both aspects, and current cognitive architectures typically have both types of control in them. The review of the stress theories will conclude by examining where control is placed and how stress influences control, and perhaps label it as Type 3.

2.3 Overlays

An overlay is a technique for including a theory of how a behavioral moderator, such as stress, influences cognition across all models within a cognitive architecture. Previous work that has been done in modeling stress has often only been developed and tested on a single model and a single task. Although implementing theories of stress as modifications to a model in a cognitive architecture is a proper first step, it falls short of the goals of an overlay.

An overlay, as we propose it, is an adjustment or set of adjustments to the parameters or mechanisms that influence all models implemented in the architecture to reflect changes due to an altered mental state or due to long term changes such as development. In many architectures there are a set of mechanisms and a number of global parameters that play a role in the model's functioning; an overlay modifies a combination of parameters and mechanisms to represent situation specific but relatively long acting changes to information processing. For example, a eye-glasses overlay would allow more inputs to be passed to the vision processor; a caffeine overlay could increase processing speed by 3% and improve vigilance by 30%. This approach keeps the architecture consistent across tasks and populations, but allows that there may be differences for individuals or groups in certain contexts, and provides a way to describe these differences. The overlay takes advantage of having the mechanisms being formally represented and used to perform all tasks.

There are at least two ways to generate overlays for pre-task appraisal as a type of stress. The first way is to examine existing theories of how stress influences cognition, and implement them in ACT-R. Migrating verbal theories into cognitive models has been done before for other theories in other areas (e.g., with development Jones, Ritter, & Wood, 2000). This process is not always completely satisfactory, as the verbal theories can be posited in vague terms, and do not always indicate how they would interact with behaviors and effects necessary to implement them. Implementing them, however, generates suggestions for improving them.

The second way to generate overlays is to examine the architecture and propose overlays based on the architecture's mechanisms and parameters. These theories can be implemented directly, but sometimes are difficult to compare with existing theories as they arise from the architecture.

A problem that can occur when the theory is more concrete, is that sometimes the verbal theory makes different assumptions about how information is processed or is represented in terms that are not easily reconciled with a particular formalism. For example, Hendy, Farrell, and East's (2001) model of stress response predicts information processing itself is decremented with stress, and theories by Canon (Cannon, 1932), Selye, and Mason in the biopsychology literature predict that performance decreases above an optimal level of stress or arousal. But these theories work only on a general level of information processing.

Even more troubling is when the theories make assumptions about processing that cannot yet be directly or routinely implemented in models or their architectures. Examples of these effects include how under stress, particularly high workload stress, tasks are deliberately shed (e.g., Parasuraman & Hancock, 2001; Wickens, Gordon, & Liu, 1998) and how negative information in particular may be lost or ignored. Both of these require more complex models and architectures to represent task load, and to be implemented they need the model to dynamically adjust its strategies, and to include a more complex representation of knowledge.

Implementing overlays is easier to do in some architectures and is harder in others. This chapter will use ACT-R as the architecture to implement the theories as overlays. However, the overlays description could be used fairly easily with other architectures. For example, COJACK (Norling & Ritter, 2004) was designed to support this, and EPIC (Kieras, Wood, & Meyer, 1995) should also support including these overlays.

3. Brief overview of ACT-R

ACT-R is a hybrid embodied cognitive architecture (Anderson et al., 2004). ACT-R specifies constraints at a symbolic level and a Bayesian based sub-symbolic level. It has perceptual-motor components as well as memory and cognitive control components. All components or modules communicate through buffers. Examples of ACT-R models are available in XX's, Y's, and Z's chapters.

3.1 The choice of knowledge to apply: U = PG – C + Noise

The cognitive control component of ACT-R is the procedural module. This module is based on the production rule framework. The basic symbolic unit is a production, which is a condition-action pair. The condition side of a production specifies zero or more buffer patterns to be matched against the contents of the corresponding buffer. If a match occurs then the production is eligible to fire and is placed in the Conflict Set. Which production actually fires on a given cycle is based on the expected utility equation, Eq. 1.

$$E = PG - C + \text{Noise} \qquad \text{Eq. 1}$$

In Equation 1 E is the expected utility of the production, P is the probability that firing this production will lead to success, G is the value of achieving the goal in units of time, and C is the expected cost in units of time from firing this production to achieving the goal. Noise from a logistic distribution is added to provide stochasticity.

ACT-R computes this sub-symbolic quantity for each production in parallel. The production with the highest utility will fire if it is above a threshold, called the utility threshold. The P and C parameters in this equation can be learned over time. If learning is on, then P is calculated by dividing the number of times the production has led to successful completion of the goal by the total number of firings of the production. C is calculated by dividing the total time from execution of this production to the successful completion of the goal by the total number of firings of the production.

The action side of a production consists of commands to zero or more modules. P and C can be learned through experience. P is the total number of successes for the production divided by the total number of successes and failures. C is the total effort (i.e., the accumulated time over all the production firings) divided by the total number of successes and failures.

3.2 Declarative knowledge as chunks

The declarative memory component in ACT-R is the declarative module. The symbolic unit is a chunk, which is a typed structure containing slot-value pairs. At the sub-symbolic level, the declarative module is activation based. The activation equation for a chunk is given in Eq. 2.

$$A = \text{Base Level} + \text{Source Spread} + \text{Partial Matching} + \text{Noise} \qquad \text{Eq. 2}$$

The activation A is composed of four parts. The Base Level represents the frequency and recency of use. The Source Spread represents the contribution of the internal and external context, by spreading activation from chunks contained in buffer chunks to the target chunk. The Partial Matching Component represents the degree to which the pattern specified by the retrieval request matches the target chunk. Noise from a logistic distribution is added to provide stochasticity.

The chunk with the highest activation will be the chunk retrieved if it is above a threshold, called the retrieval threshold. The time for a retrieval is directly related to the activation of a chunk; the higher the activation the faster the retrieval.

The base level activation of a chunk is computed by equation Eq. 3.

$$B_i = \ln\left(\sum_{j=1}^{n} t_j^{-d}\right) + C \qquad \text{Eq. 3}$$

In this equation B_i is the Base Level of the target chunk i, t_j is time since the jth retrieval of chunk I, n is the total number of retrievals for chunk I, d is the decay rate, and C is a constant (called the Base Level Constant)

The Source Spread activation is the sum of strengths of association between chunks contained in slots of the buffers and the target chunk. For each buffer, the strengths of association are weighted by the source spread for each buffer divided by the number of chunks in the buffer spreading activation.

The activation of a chunk as noted in Eq. 2 is partially based on the Source spread. ACT-R includes a parameter W that represents the goal's activation. This value has been used to represent working memory capacity (Lovett, Reder, & Lebiere, 1999), and shown to correlate with performance on a problem-solving task.

3.3 A theory of perception and motor movement

The perceptual components include the vision module and the auditory module. The vision module contains a "where" and a "what" system. The "where" system generates a location chunk in response to a pre-attentive search for one or more features such as shape and/or color. The "what" system moves visual attention to the location chunk generated by the "where" system and encodes the features at that location into a visual object.

The motor components include a manual module and an eye movement mechanism called EMMA (Salvucci, 2001), which can be incorporated into the vision module. EMMA calculates the time to move the eyes. This time is the time to prepare the movement plus the time to execute the movement. The execution time is calculated by Eq. 4 shown below.

$$T_{exec} = T_{init} + T_{base} + (\text{Saccade-rate} * \text{distance}) \qquad \text{Eq. 4}$$

In this equation the total execution time is the sum of the programming time (T_{init}), the base movement time (T_{base}), and the distance to move the eyes times the saccade rate.

EMMA also calculates the encoding time of an object based on eccentricity from the fovea's location and frequency of encoding as given in Eq. 5.

$$T_{enc} = K*[-\log f_i]*e^{k*ecc-I} \qquad \text{Eq. 5}$$

In this equation, T_{enc} is the encoding time, K scales the encoding time, F_i is how many times the object has been encoded, ecc-i is the eccentricity of the object, and k is a scaling constant.

4. The theories of stress and cognition

We present a range of overlays of stress to consider. The overlays were generated in two ways. The first group of overlays is based directly on existing theories of how cognition is influenced by stress. We have tried to choose theories that speak to pre-task appraisal, but in some cases it is difficult to understand which type of stress the theory is referring to, and to differentiate workload stress from mental demands and from task appraisal. The second group of overlays contain simpler ones generated by examining ACT-R's mechanisms.

Table 1 provides a summary of these theories as a preview and organizer. In several cases there are multiple ways to implement these theories. Where this occurs we sometimes include multiple variants. Some are the theories sound different but become the same when we implement them. This may be due to our limitations, but we can hope that it is because they are attempting to describe the same phenomena.

We implement the overlays as percentage changes where we can because some models start with base differences from ACT-R's default settings. This approach may also allow overlays to be combined.

The overlays are provide in a format that can be loaded to modify models in ACT-R 6, and we are in the process of using these overlays to predict performance under stress (e.g., Ritter, Ceballos, Reifers, & Klein, 2005).

We provide parameter setting in most cases not as a firm stance, but to implement the theory (we have to have a number), and to indicate the range of values we are considering. These numbers serve as a necessary starting point because we will be using them to fit and to test. We admit that few of these overlays are likely to optimal. An implementation of most of these overlays are at acs.ist.psu.edu/cafenav/overlays/ .

4.1 Wickens' theories

We have taken Wicken's theories of stress from Wickens, Gordon, and Liu (1998). They note (p. 383) that it is difficult to predict the "amount of stress" (their quotes) for psychological stressors in any particular circumstance because of individual differences in cognitive appraisal. These differences can arise through changes in information processing due to how the task is performed (allowing more or less time to appraise the situation), how the task is appraised due to level of expertise, and whether one is in control of the situation. They do, however, go on to provide some theoretical statements that can be used to implement overlays.

Further in their review, Wickens et al. (1998) note perceptual narrowing (or tunneling) as an effect of stress (over arousal). We take perceptual narrowing to be where the effective perceptual field becomes smaller with stress, that items to the periphery become less attended. The item focused on is typically the cause of stress or related to relieving this stressor. Cognitive tunneling can also occur, where a limited number of options are considered.

Table 1. Summary table of the proposed overlays to implement pre-task appraisal (stress) in ACT-R. Challenged is taken to be ACT-R 5 defaults.

Overlay and Major Effects	Implementation of the threatening appraisal
Wickens-PT Perceptual tunneling	**Variant A.** Visual attention latency goes up by 15%. For default ACT-R, 0.085 ms to 0.0978 ms.
	Variant B. Visual distance goes down by 20%. For default ACT-R, this is 15 inches to 12 inches.
	Variant C. The objects available from vision (the visicon) are modified to allow only items within 10 deg. of the fovea.
	Variant D. For use with EMMA: Saccade rate decreased by 50% and fixation times increase by 100%. Defaults are given in Eq. 4.
Wickens-CT Cognitive tunneling	**Variant A.** Declarative retrieval threshold increases by 20% or 2 (whichever is greater). Default is 0.
	Variant B. Procedural threshold goes up by 20% or 2 (whichever is greater). Default is 0.
	Variant C. Noise is decreased for both declarative and procedural knowledge retrieval processes; ANS and EGS decrease by 50%. For default ACT-R, these are both 0.
Wickens-WM Working memory decreases	**Variant A.** W goes to 0.8 * W. For default ACT-R, 1.0 to 0.8.
	Variant B. The baselevel activation for all declarative memory elements is decremented by 20%. For default ACT-R, this is 0.
	Variant C. Activated memory elements decay faster (parameter BLL increases by 25%, default is nil, but, when used, most models use 0.5).
Wickens-SS Favor low cost strategies	PG - C is used to choose a rule, modified to be PG – 1.2 C.
Intrusive thought Includes a distracter rule	Two simple rules are added to the model that interrupt the models flow and activation of chunks.
Hancock-Szalma-IA Information assimilation decreases with stress	**Variant A.** Fixation times increase (EMMA) by 25%. For default ACT-R with EMMA, time is given in Eq 5.
	Variant B. Lower activation of visual objects by 10% of the base activation. Default in Emma is 1.0.
Avraamides Procedural knowledge noise increases with stress	EGS goes from 0.1 (challenged) to 1.0 (threatened). ACT-R default is 0. A few other parameters are changed as noted in the overlay for both settings.
Belavkin Dynamically moderate procedural noise based on success rate	Value of goal is modified from base value dynamically. See Belavkin and Ritter (2004), for details.
Processing speed Modifies processing speed	**Variant A.** Default rule application time (DAT) modi-fied by 120%. For default ACT-R from 0.05 s to 0.06 s.
	Variant B. Increase all rule application time by 25%. For default ACT-R, 50 ms to 62 ms.
	Variant C. Add noise to processing speed. This would add a new variable to ACT-R.
Learning rate Modifies procedural learning rate	Modifies procedural learning by 15 %. For default ACT-R, this is off (nil)

Wickens-PT. Perceptual tunneling can be implemented several ways. One way is to vary the default distance from the screen. This effectively makes objects on the periphery less visible. Another way is to modify the visual attention latency. This makes moving attention to the periphery slower, and some agents would use information less from the periphery because it is harder to get, and would miss more changes there. Another way is to limit what is in the perceptual field by decreasing its width; this is slightly more difficult to implement than the approaches put forward here, but is quite doable.

Finally, another approach to create perceptual tunneling is to increase the saccade time. ACT-R 5 does not include a theory of eye movements, but is based on a theory of moving visual attention. Including an extension called EMMA (Salvucci, 2001) allows eye-movements to modeled and to be modified by overlays. These overlays as a set modify Type 2 mechanisms.

Wickens-CT. To implement cognitive tunneling, the declarative and procedural retrieval thresholds in ACT-R can be modified by the overlays to represent a greater reliance on well known and well-practiced knowledge. Good general practice involves setting the retrieval threshold below the base level activation by 50%. Alternatively, noise in the procedural rule application process can be decreased (i.e., activation noise and expected gain noise), which would lead to only the most well-practiced materials being retrieved and applied. These overlays modify central cognition, a Type 1 mechanism.

Wickens-WM. Wickens et al. (1998, p. 385) and others note that working memory capacity appears to decrease under stress. Under stress, working memory appears to be less available for storing and rehearsing information, and less useful when performing computations or other attention-demanding tasks. Wickens et al. go on to note that long-term memory appears to be little affected and may even be enhanced (although, some of the reasoning effects noted below will perhaps mitigate this effect, such as focusing on well learned knowledge, which also implies focusing less on less well known knowledge, which is using less of long term memory!).

The implementation of this theory is not completely straightforward. While it appears clear, it is not clear whether working memory capacity is part of the ACT-R theory. Lovett and colleagues (2000) showed how working memory can be modeled within the ACT-R architecture and proposed the W (goal activation) parameter as a measure of individual working memory capacity. This parameter, W, only affects the spreading activation term of the ACT-R activation equation. But many, perhaps most ACT-R models do not use spreading activation. That is, most ACT-R models do not explicitly set up the goal with the associated chunks so that activation can spread, but instead rely on the base level of activation of memory items to compute how memory items are retrieved. In addition, learning influencing spreading activation is no longer part of the theory in ACT-R 6. However, when appropriate, this parameter can be used as an overlay parameter, but it will not affect models that do not use W in this way. Thus, another way to implement working memory decrements then is to decrease the base-level activation of all memory elements when stressed by a percentage.

Another less tested approach is to decrement the basic (base level) activation for all memories. A promising approach is to modify the decay rate of working memory objects. This is interesting, as this theory is sensitive to many known effects on working memory, including that it would predict that that the time to report objects in working memory will influence the measurable size of memory.

There are two other ways that working memory could be effectively decremented. One way is to increase the retrieval threshold, which would make less memories available. This is included in another overlay. Another way is to limit the number of items allowed in a chunk. This would be much more difficult to implement, particularly to support its wide application. All of these overlays modify central cognition, and thus influence a Type 1 mechanism.

Wickens-SS. Wickens et al (1998, p. 385) also note that under stress there are sometimes strategic shifts, with an emphasis to "do something, now!" (their quotations). This effect is interesting, as other authors also sometimes note under stress that operators freeze, although this may not be the same type or the same amount of stress. Although this theory may be incompletely defined for instantiation in ACT-R, we attempt to create an appropriate formalization.

The overlay here (strategy-shift) shifts the expected gain and expected gain equation to favor strategies (rules) with low expected cost. This encourages the model to choose rules that do something 'now' over rules and strategies that have high payoff but also have high costs (which are in units of time).

There will be a problem applying this overlay if the models are simple. That is, this overlay only changes behavior if there is another strategy to shift to. This overlay should be seen as a fairly tentative theory.

This mechanism influences central cognition, but it is sensitive to strategies that are available. This is not distributed, but is a change that requires additional knowledge (strategies) to be available to have it influence cognition.

4.2 The task as stressor—Hancock and Warm (1989)

Hancock and Warm (1989) describe the effect of stress on task performance as an individual's interest in maintaining an optimal amount of information flow. They note several effects, including that "physiological compensation is initiated at the point at which behavioral response reaches the exhaustive stage." So, as stress increases, the agent modifies its cognitive efforts, then its physiology changes to support these efforts, and then, after a sufficient period of time, there will be a catastrophic collapse due to exhaustion of the physiological level. The task itself should be seen a source of stress, with sustained attention as the stress generator. For (well-practiced) automatic tasks, there is little effect of stress on performance and performance of the task does not increase stress.

The other reusable aspect of their theory is an explanation about why heat stress on a simple task can be better predicted than noise stress. Their approach is to understand the input, the adaptation, and the output (here, we would focus on the effect of the adaptation to the information processing and output mechanisms). Heat stress has a fairly simple input description, and its effects on cognition, physiology and adaptation appear to be, they note (p. 532), direct and straightforward. There are few strategies to cope with heat and these strategies are simple and do not modify cognition. We would add that the effects of heat (or cold) on cognition are relatively monotonic over time and over changes towards extreme temperatures. The empirical results they review show a very nice area where physiology directly affects cognition. Cognition directly suffers when thermoregulatory action can no longer maintain core body temperature. They point out that environmental auditory noise is less easy to characterize, and that adaptation to noise is more complex. The adaptation varies more across individuals and is more complex cognitively and physiologically. Pre-task appraisal varies even more across individuals, and the coping strategies vary more and use cognition much more. Thus, pre-task appraisal will be more difficult to model because task appraisal is a more dynamic and more knowledge-based moderator.

We do not take away an overlay from their paper, but we take away the three part description of input, adaptation, and response. Although we have neglected to model the effects of tasks as stressors themselves, we recognize that modeling the effects of a task as a stressor would be an interesting and admirable next step in the effort to model the effects of stress. We also do not yet model, but should put on our scorecard, that the task itself, perhaps even when challenging and not threatening, will serve as a stressor over time. This is supported by a review of caffeine, which summarizes that without caffeine, performance on a vigilance task decreases over time even for motivated subjects (Morgan, Ritter, Stine, & Klein, submitted). This theory also predicts that performance and resources will degrade faster when performing more complex tasks. We also gain a greater understanding of the types of moderators; those with multiple coping strategies will be more difficult to model.

4.3 Decreased attention—Many researchers

Several theories describe the effect of stress on cognition as decreased attention. Hancock (1986) reviews several and puts forth his own. ACT-R includes several ways that attention can be modified.

Working memory capacity is a type of attention that is also a parameter that can be modified in ACT-R. We use it in the Wickens-WM overlay, discussed above. All of the overlays developed here related to attention predict that the more attention the task demands, the more susceptible performance is to stress, which is consistent with the literature.

Intrusive thought as dual task. We can add a secondary task to the model to simulate worry. In this case, stress causes a dual task to appear. This has been implemented as a pair of productions that represents the use of working memory to do processing about the stressor and task. When these rules are chosen, they take time from the primary task, allow the declarative memory of the primary task to decay over the time that they take to apply, and can leave the working memory in an incorrect state if they are interrupted themselves. These effects can be further moderated by the rule's strength. This approach to modeling anxiety is consistent with theories of math anxiety and other studies of anxiety (e.g., Ashcraft, 2002; Cadim, Maass, Rosabianca, & Kiesner, 2005; Sarason, Sarason, Keefe, Hayes, & Shearin, 1986).

We have used an intrusive thought as a possibility before (Ritter, Reifers, Klein, Quigley, & Schoelles, 2004) by including an additional rule set that can apply, but otherwise does nothing task related. Further versions could be implemented that worry directly about the task components, which would have a less negative effect, but which could also bias decisions or modify processing.

This overlay does not directly modify a mechanism, per se, but its effects are felt primarily in central cognition. In this case, perhaps, this overlay is not classifiable as a type 1 or type 2 overlay.

4.4 Perceptual narrowing—Hancock and Szalma (2003)

Hancock and Szalma (2003) note that stress influences sensory and perceptual capacities, "which results first in a diminution and then a failure of information assimilation", and that "stress depletes resource-based processing of higher-level functions (e.g., problem solving)." While these are not quantitative predictions yet[1], we can create an overlay that modifies the sensory and perceptual capabilities. We can also attempt to explore how this theory is different than Wicken's (and others') perceptual narrowing.

An overlay of information assimilation could modify how quickly the visual attention can shift. Thus, with increased stress, the number of objects that can be fixated upon in a given time period decreases. This is similar to Wickens-PT-A.

Hancock-Szalma-IA. A more advanced approach to perceptual narrowing than in the Wickens-PM overlay is to use the EMMA extension to ACT-R. EMMA incorporates a theory of eye movements into ACT-R. This overlay of information assimilation modifies in ACT-R the time to encode a visual object (see Eq. 4) which is equivalent to the fixation time. Thus, with increased stress, the number of objects that are fixated upon in a given time period decreases.

Another variant that is possible is simply to lower the activation of visual working memory objects, which would make them less available and take longer to manipulate. This variable is new to ACT-R 6. This overlay decreases the activation of visual objects by 10% of the base level constant. Thus, this overlay modifies peripheral, Type 2 mechanisms.

4.5 Variance in behavior—Avraamides

Increased procedural variance. Avraamides suggested that higher levels of stress increased the variance used in choosing which procedural knowledge to apply. In initial models of the serial subtraction task increasing the procedural knowledge selection noise (EGN in ACT-R 4, EGS in

[1] Indeed, Hancock (personal communications, December, 2004) noted that he thought that there are no theories of stress complete enough to directly implement in a cognitive architecture.

ACT-R 5) shifted the model's behavior so that more mistakes were made[2]. The reason to include more noise was so that when threat appraisal was selected in the model, the default value of EGN was changed to a greater number (1.0 vs. 0.1) to simulate a state where the procedural knowledge was applied less accurately in the threatened state (Ritter, Avraamides, & Councill, 2002; Ritter et al., 2004). This overlay helped the model predict performance on a single task fairly well. This overlay would, however, increase the application of less than optimal knowledge, but its effects would be more noticeable when the knowledge is not well learned. The explanation then, is that with expertise, the effect of noise is still there, but that noise has a lesser effect on experts whose knowledge may be more differentiated and has greater strength than novices have. This overlay, and the next, both modify central cognition, thus influencing a type 1 mechanism.

Decreased procedural variance. Increased noise (EGS) will lead to using different knowledge sources and trying new (less well known) strategies more. This is at odds with many theories of stress, which postulate that with increased stress operators rely more on well-learned procedural knowledge and do not try out new strategies. This alternative, inverse overlay would, however, increase the application of less than optimal knowledge, but its effects would be more noticeable when the knowledge is not well learned. This is included as Wickens-CT-A.

4.6 Local changes to motivation—Belavkin and Ritter (2004)

Belavkin and Ritter (2004) posited a theory of how motivation changes with success and failure based on a review of the emotions literature. Belavkin has created an overlay that modifies ACT-R's expected gain noise value so that with each success on a task, this noise value goes down. This has the effect of the problem solver paying more attention to their knowledge, when it has been successful.

When the problem solver has recently been unsuccessful, the noise value goes up. This increases the noise in knowledge application, leading to less rational choices of which knowledge units to apply (in the case of ACT-R, these are rules). If the model is caught in a local minimum in the weights to the knowledge units, this approach will help it move to a new state. This overlay applied to a model has successfully been shown to model the Yerkes-Dodson (1908) mice data better than an unmodified ACT-R model (Belavkin & Ritter, 2004). This overlay modifies a type 1 mechanism.

Belavkin-moderated EGN. This overlay (www.cs.mdx.ac.uk/staffpages/rvb/software/optimist) is consistent with Avraamides' overlay, but is more dynamic. Avraamides' overlay predicts that noise increases with a threatening appraisal. The Belavkin overlay predicts that poor performance is also a stressor that increases knowledge choice noise, and predicts that noticing the performance as being poor could lead to appraising the task as threatening. This overlay also increases the application of less than optimal knowledge, particularly when the knowledge is not well learned and the problem solver is not successful.

4.7 Theories grounded in architectural mechanisms

The use of the ACT-R architecture allows other theories to be generated based on the architecture itself. The major parameters in ACT-R include working memory capacity, processing speed, the declarative and procedural retrieval thresholds, expected gain noise, and the rate of learning. Several of these parameters have not been used to implement an existing theory of stress in an overlay. Because, as parameters, they suggest where changes occur, they are used to create overlays here. Their lack of use in other overlays could be because we have a limited review, or because these parameters are not seen as being influenced by stress. Both of these overlays modify type 1 mechanisms, but there are other parameters in the peripheral mechanisms that could be modified.

Processing speed. We propose three ways to implement changes to processing speed. Variant A modifies the processing speed by decrementing the default time to apply a rule. The base speed is used for modeling challenging conditions (currently at 50 ms/rule application), and the processing

[2] A few other parameters were changed for both conditions, including partial matching and enabling rational analysis. Details are available in the overlay.

rate is dropped by 25% to model the effect of threatening appraisals. A likely secondary aspect of this overlay is that the error rate may go up slightly because working memory will have more time to decay during a now longer task performance time. This increase in errors might be small enough that it is not a reliably noticeable difference, and some rules will not use the default application speed, but will have their own speed. Variant B modifies the processing speed for all rules. Variant C adds noise to the processing speed, and requires a new variable.

Learning rate. Neither the procedural nor declarative learning rate has been used by the overlays above. The procedural learning rate, a simple procedural strengthening, in addition to helping with learning, also appears to help a model decrease its error rate in serial subtraction task over a four-minute block (Bansal, 2002). The learning rate overlay determines how quickly the model can learn to discriminate between two or more productions. This is accomplished by scaling the learning of the probability parameter in the Utility equation.

4.8 Testing these overlays

The overlays need to be applied to a wide range of tasks, and the results compared to subjects' task performance. A large battery of tasks will be important because on a single task some of these overlays may make similar predictions on a single task, and thus will need to be tested with a complete battery of tests are given to people who are stressed.

The complexity of this problem, because it requires a suite of tasks, data, and models, will require reuse of models and tasks. Preliminary data (Ritter et al., 2005) on a set of tasks shows differences that should help differentiate these overlays, and that task-related stress was present.

5. Summary

This set of overlays provides a rich and full set of theories to test. Implementing and testing them should tell us a lot about how cognition and performance vary on these tasks.

5.1 Theories of stress are not complete

As a set, these overlays tell us how stress has been conceptualized. A summary of these overlays and their current implementations are shown in Table 1. The table shows that most of the theories modify only one aspect of cognition. Nearly all influence central cognition and only a few affect periphery processes. In particular, none of this set affect the motor processor. The areas where these theories are not all complete can be seen. For example, we know that mental arithmetic is influenced by stress (Ashcraft, 2002), but the perceptual narrowing theory and several other theories do not predict an effect of stress on serial subtraction (which we know exists, Tomaka et al., 1993). For other overlays, similar tasks can be proposed where the theory predicts that stress will not influence performance. These theories are being designed to be combinable, and we will need to investigate their combinations.

These overlays considered here are static overlays (except for Belavkin's OPTIMIST), representing the state of processing in a challenged (or neutral) and in a threatened state, and are fixed across time. Stress is probably not a binary effect. Responses to stress are not static, and thus an area for future work will be making the response dynamic with respect to time, showing where stress comes from, and showing how task performance can ameliorate the effects of stress or contribute to it. In time, it is clear that stress has a range of values and a more dynamic nature than the theories and these overlays provide. Future work will have to grapple with the additional difficulties of creating a model of stress that dynamically adjusts to the effect of the task itself and of stress on the task. The testing and comparison of these more complex theories is not possible with our current understanding. Computing power to run the models also appears to be a limitation—to run the models (set to the individual differences for 135 subjects, perhaps) over 5 tasks for 10 overlays is difficult enough—creating dynamic overlays would combinatorially compound this problem. Where there is one overlay that is dynamic and we will use it (Belavkin), we do not attempt to create new dynamic overlays here.

5.2 Introducing another type of mechanism

This review suggests that it is time to consider again the embodied cognition issue, and this time from a physiological perspective. Creating a dynamic overlay and implementing the effects of behavior moderators will soon require modeling the body itself and how changes to the physiology of the body influence cognition.

This introduces a Type 3 mechanism to Gray's (Chapter 3) taxonomy of control mechanisms. Type 3 is related to physiology and how it supports cognition. (It could be called a is sub-sub-symbolic level.) The control is not distributed, but diffuse, complex, and interactive with the environment including time. Physiological theories are not implemented here because of their complexity. They suggest a type of mechanism that is peripheral and distributed across cognitive mechanisms. It influences other mechanisms due to changes in time, changes in other physiological processes, and due to how cognitive and perceptual mechanisms (both central and peripheral) use resources.

5.3 Time: An additional aspects to mechanisms

This review suggests that there is an additional aspect to mechanisms, which is how the mechanisms are sensitive to time. Many stress theories predict that people are sensitive to time. That is, the theories predict that cognitive mechanisms vary as time passes. Hancock and Warm (1989), for example, explicitly note this. Most models in most architectures do not take account of time's influence on task performance. For an example of a model that is influenced by time, see Gunzelmann, Gluck, Van Dongen, O'Conner, and Dinges (in press). Their model modifies the value of the goal over time, representing fatigue. These overlays will also need to incorporate aspects of how time is spent (e.g., sleeping) and time-on-task for a single, particular task will influence task performance.

5.4 The future

Creating an overlay or set of overlays that model the effects of stress is a first step. After creating these and testing them, there are several lines of research that can be investigated. First, we would hope to create other global overlays modeling other psychological phenomenon demonstrating that the concept of overlays in a cognitive architecture is indeed useful. For example, overlays could be extended to study extreme levels of stressors: of fatigue, of heat, and of dosages of caffeine.

Second, these stress overlays might also be further extended. They could be extended to model different levels of stress or individual differences such as personality type. They could also be refined. For example, the distracter thought overlay could have several different thoughts, some not focused on the task, which would slow down the model and thereby reduce the activation of working memory, and other thoughts that might be more task related, and would slow down the task but raise the activation of particular task component memories, and lead to different learning or performance.

Finally, these overlays have implications on other aspects of cognition, for example, how situation awareness is influenced by stress and how to ameliorate the effects of stress on situation awareness. In the case of situation awareness, it is straightforward to compute how well the model's representation of the world matches the world, which is level 1 of Endsley's (1997) situation awareness. It is also relatively straightforward to compute how often and how well the model updates its model of the world (level 2 and 3, what objects are doing, and what objects will do). Level 1 SA can be computed for most models. Their representations of the world will not be as accurate as humans', but this computation could be done, and a multi-variable qualitative summary could be provided. Level 2 and 3 are more difficult. Many models do not update their mental models of the world except in a reactive way. When modeling situation awareness this does not appear to be an adequate technique. If SA is to be modeled appropriately then there will need to be a more dynamic and proactive model. When modeling situation awareness, this does not appear to be an adequate approach. If SA is to be modeled appropriately then there will need to be a more dynamic and proactive model. It will also be necessary to define a measure of SA that summarizes this type of dynamic cognition with respect to level 2 and 3. These overlays suggest that SA would be influenced in different ways and in different amounts depending on each theory of how stress influences cognition, and they suggest rather different remediation strategies.

Granted, the goals are ambitious, but the possible implications and impact seem to be worth exploring. The next step here is to see how compare the models with overlays to data, including the differences in error rates and error types that these overlays predict.

References

Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of the mind. *Psychological Review, 111*(4), 1036-1060.

Ashcraft, M. H. (2002). Math anxiety: Personal, educational, and cognitive consequences. *Current Directions, 11*(5), 181-185.

Bansal, A. (2002). *A case for user interfaces for cognitive models: An example*. Unpublished MS thesis, Computer Science and Engineering, Penn State.

Belavkin, R. V., & Ritter, F. E. (2004). OPTIMIST: A new conflict resolution algorithm for ACT-R. In *Proceedings of the Sixth International Conference on Cognitive Modeling*, 40-45. Mahwah, NJ: Lawrence Erlbaum.

Cadim, M., Maass, A., Rosabianca, A., & Kiesner, J. (2005). Why do women underperform under stereotype threat? *Psychological Science, 16*(7), 572-578.

Cannon, W. B. (1932). *The wisdom of the body*. New York, NY: Norton.

Endsley, M. R., & Jones, W. M. (1997). Situation awareness information dominance & information warfare (Technical report No. AL/CF-TR-1997-0156): United States Air Force Armstrong Laboratory.

Gunzelmann, G., Gluck, K. A., Van Dongen, H. P. A., O'Conner, R. M., & Dinges, D. F. (in press). A neurobehaviorally inspired ACT-R model of sleep deprivation: Decreased performance in psychomotor vigilance. In *Proceedings of the Twenty-Seventh Annual Meeting of the Cognitive Science Society*. Mahwah, NJ: Lawrence Erlbaum.

Hancock, P. A. (1986). The effect of skill on performance under an environmental stressor. *Aviation, Space, and Environmental Medicine, 57*(1), 59-64.

Hancock, P. A., & Szalma, J. L. (2003). Operator stress and display design. *Ergonomics in Design, 11*(2), 13-18.

Hancock, P. A., & Warm, J. S. (1989). A dynamic model of stress and sustained attention. *Human Factors, 31*(5), 519-537.

Hendy, K. C., Farrell, P. S. E., & East, K. P. (2001). An information-processing model of operator stress and performance. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload, and fatigue* (pp. 34-80). Mahwah, NJ: Lawrence Erlbaum.

Jones, G., Ritter, F. E., & Wood, D. J. (2000). Using a cognitive architecture to examine what develops. *Psychological Science, 11*(2), 93-100.

Kieras, D. E., Wood, S. D., & Meyer, D. E. (1995). Predictive engineering models using the EPIC architecture for a high-performance task. In *Proceedings of the CHI '95 Conference on Human Factors in Computing Systems*, 11-18. New York, NY: ACM.

Lovett, M. C., Daily, L. Z., & Reder, L. M. (2000). A source activation theory of working memory: Cross-task prediction of performance in ACT-R. *Journal of Cognitive Systems Research, 1*, 99-118.

Lovett, M. C., Reder, L. M., & Lebiere, C. (1999). Modeling working memory in a unified architecture. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 135-182). New York, NY: Cambridge University Press.

Morgan, G. P., Ritter, F. E., Stine, M. M., & Klein, L. C. (submitted). The cognitive effects of caffeine: Implications for models of users.

Newell, A. (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.

Norling, E., & Ritter, F. E. (2004). A parameter set to support psychologically plausible variability in agent-based human modelling. In *The Third International Joint Conference on Autonomous Agents and Multi Agent Systems (AAMAS04)*, 758-765. New York, NY: ACM.

Parasuraman, R., & Hancock, P. A. (2001). Adaptive control of mental workload. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload, and fatigue* (pp. 305-320). Mahwah, NJ: Lawrence Erlbaum.

Pew, R. W., & Mavor, A. S. (Eds.). (1998). *Modeling human and organizational behavior: Application to military simulations*. Washington, DC: National Academy Press. books.nap.edu/catalog/6173.html.

Quigley, K. S., Feldman Barrett, L. F., & Weinstein, S. (2002). Cardiovascular patterns associated with threat and challenge appraisals: A within-subjects analysis. *Psychophysiology, 39*, 292-302.

Ritter, F. E. (1993). Three types of emotional effects that will occur in cognitive architectures, *In Workshop on architectures underlying motivation and emotion (WAUME93). School of Computer Science and Centre for Research in Cognitive Science, University of Birmingham, UK*.

Ritter, F. E., Avraamides, M., & Councill, I. G. (2002). An approach for accurately modeling the effects of behavior moderators. In *Proceedings of the 11th Computer Generated Forces Conference*, 29-40, 02-CGF-100. Orlando, FL: U. of Central Florida.

Ritter, F. E., Ceballos, R., Reifers, A. L., & Klein, L. C. (2005). Measuring the effect of dental work as a stressor on cognition (Tech. Report No. 2005-1): Applied Cognitive Science Lab, School of Information Sciences and Technology, Penn State. acs.ist.psu.edu/acs-lab/reports/ritterCRK05.pdf.

Ritter, F. E., Reifers, A., Klein, L. C., Quigley, K., & Schoelles, M. (2004). Using cognitive modeling to study behavior moderators: Pre-task appraisal and anxiety. In *Proceedings of the Human Factors and Ergonomics Society*, 2121-2125. Santa Monica, CA: Human Factors and Ergonomics Society.

Salvucci, D. D. (2001). An integrated model of eye movements and visual encoding. *Cognitive Systems Research, 1*(4), 201-220.

Sarason, I. G., Sarason, B. R., Keefe, D. E., Hayes, B. E., & Shearin, E. N. (1986). Cognitive interference: Situational determinates and traitlike characteristics. *Journal of Personality and social Psychology, 51*(215-226).

Silverman, B. G. (2004). Human performance simulation. In J. W. Ness, D. R. Ritzer & V. Tepe (Eds.), *The science and simulation of human performance*. Amsterdam: Elsevier. www.seas.upenn.edu/~barryg/Ch9-final.pdf.

Tomaka, J., Blascovich, J., Kelsey, R. M., & Leitten, C. L. (1993). Subjective, physiological, and behavioral effects of threat and challenge appraisal. *Journal of Personality and Social Psychology, 65*(2), 248-260.

Wickens, C. D., Gordon, S. E., & Liu, Y. (1998). *An introduction to human factors engineering* (3rd ed.). Addison-Wesley: New York, NY.

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit formation. *Journal of Comparative Neurology and Psychology, 18*, 459-482.