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A cognitive modeling account of simultaneous learning and fatigue effects

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Abstract

Current understanding of sources of fatigue and of how fatigue affects performance in prolonged cognitive tasks is limited. We have observed that participants improve in response time but decrease in accuracy after extended repetitive work in a data entry task. We attributed the increase in errors to accumulating fatigue and the reduction in response time to learning. The concurrent effects of fatigue and learning seem intuitively reasonable but have not been explained computationally. This paper presents a cognitive computational model of these effects. The model, developed using the ACT-R cognitive architecture (Anderson et al., 2004; Anderson & Lebiere, 1998), accounts for learning and fatigue effects through a time-dependent modification of architectural parameters. The model is tested against human data from two independent experiments. Best fit to human accuracy and total response time was found from a modulation of both cognitive and arousal processes. Implications for training and skill acquisition research are discussed.
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1. A cognitive modeling account of simultaneous learning and fatigue effects

Fatigue is a complex concept that overlaps multiple areas of science, from physiology and sports medicine to psychology and therapy. Although fatigue is usually associated with decrements in performance, the construct of fatigue is imprecise, not well defined, and might have effects beyond simple performance decrements. There are at least three types of fatigue that are active areas of scientific research: sleep deprivation that produces a disruption in the normal circadian rhythms (Gawron, French, & Funke, 2001; Gunzelmann et al., 2007), physical fatigue that results from increased time spent performing physical work (Gawron et al., 2001), and mental fatigue that results in a reduction of the capacity to perform an activity as a result of extended time spent on mental work (Bartlett, 1953). The type of fatigue that we address in this paper is mental fatigue (hereafter, *fatigue*). Although a real-world situation could involve both physical and mental activities, Healy, Kole, Buck-Gengler, and Bourne (2004) have concluded that mental fatigue, not physical fatigue, is often responsible for the increase in errors in repetitive tasks.

On one hand, fatigue effects might be attributed to limitations on cognitive processes such as attention. For example, some models assert that cognitive resources are needed during task performance and that there is a limited amount of such resources to expend in the task (Wickens, 1984). Thus, monotonous and prolonged perceptual processing depletes this pool of resources, making it hard to maintain attention (Parasuraman, 1986), often resulting in habituation (Mackworth, 1969). On the other hand, fatigue effects might be explained with arousal theories that argue that

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performance decrements are due to the lack of stimulation needed to maintain alertness (Ballard, 1996). Often, sustained repetitive tasks are boring (Hoffman, Sherrick, & Warm, 1998), producing decreases in arousal resulting in performance decrements (Mackworth, 1969). There is clearly a need to better understand these two possible explanations: fatigue as a cognitive process (e.g., attention) and fatigue as an arousal process.

Computational cognitive models can help formalize and integrate the factors that result in human fatigue, as well as serve as prediction performance tools. A key difference between the models developed by others and the one we present in this paper is that the present model derived directly from a behavioral pattern we have observed in a number of experiments incorporating extended task performance, which resulted in both beneficial and deleterious effects on performance (Healy et al., 2004; Kole, Healy, & Bourne, 2008). Beneficial effects, demonstrated as a decrease in response latency over time, result from general skill acquisition and from specific learning or repetition priming attributable to the repeated occurrence of stimuli and responses. Deleterious effects, demonstrated as an increase in errors over time, have causes that are less clear, but might be attributed to *fatigue* or fatigue-like processes such as boredom, task disengagement, or loss of attention that builds across trials. Although most of the cognitive models would be able to (in different ways) explain the increase in errors over time, none of the existing models of fatigue seems able to account for the concurrent and gradual effects that extended task practice has on learning and fatigue.

We propose that mental fatigue is generated by the integration and tradeoff of cognitive and arousal processes. In this research we aim to provide a concrete definition of these processes and their modulation of skill acquisition in repetitive tasks. Specifically, we propose a construct of fatigue developed and tested through an empirically-based cognitive modeling approach. We make use of mechanisms defined in the ACT-R cognitive architecture (Anderson et al., 2004; Anderson & Lebiere, 1998) to reproduce the simultaneous speedup and increase in errors observed in a data entry task (Healy et al., 2004; Kole et al., 2008). One could present an explanation of the concurrent learning and fatigue effects as the result of strategic control, where a human decides to adopt diverse strategies to place his or her own performance at different gains of speed at the cost of reducing accuracy (and vice-versus) (Pachella, 1974). However, rather than a strategic shift reflecting a speed-accuracy tradeoff adopted by the participants, we view the change in speed and the change in accuracy as reflecting a modulation of fatigue on the learning process. We will demonstrate that the concurrent learning and fatigue effects are the result of permanent learning critically present in extended repetitive tasks: the result of a more or less irreversible modification of the execution process, modulated by the level of arousal.

Task speedup with extended practice has been studied extensively in ACT-R models of learning and skill acquisition (e.g., Anderson, Fincham, & Douglass, 1999; Ritter & Schooler, 2001; Taatgen & Lee, 2003). The increase in errors that results from prolonged work, however, is rarely explained using cognitive modeling (Gunzelmann et al., 2007), and the simultaneous speedup and increase of errors with extended practice has not been explained with cognitive models at all. Thus, in this paper our theoretical account is that the concurrent speedup and increase in errors together arise from a combination of fatigue-induced changes in speed of learning and in processing capacity. These two mechanisms trade off and ultimately make people both faster and less accurate. A model of fatigue developed in ACT-R will be used to predict human data across two behavioral data sets. We will demonstrate how ACT-R can account for the effects of fatigue through time-varying changes to a subset of some central parameter values. Using the ACT-R mechanisms, we will demonstrate that fatigue results from the manipulation of motivation or level of arousal, which modulates cognitive functions, such as the maintenance and prioritization of goals and attention to relevant versus irrelevant information. Finally, we will discuss implications of the model for research on skill acquisition and training in general.

2. Cognitive models of fatigue

Computational cognitive models of fatigue are not common. Initial work in this area was done by Jongman (1998). She proposed an ACT-R model of mental fatigue in the Sternberg (1966) memory search task that consisted of performance-related decrements to cognitive control (in this particular case defined as the inhibition of interfering processes and stimuli, W parameter) and to different levels of affective control (defined as motivation, G parameter). The model worked on two different strategies that were advantageous for both accuracy and speed. Interestingly from our perspective is that the model predicted an early switch from faster and more accurate responses to slower and less accurate responses as the motivational parameter (G) decreased. The model also predicted slower and less accurate responses as the cognitive control parameter (W) decreased. Thus, Jongman's ACT-R model does not predict the simultaneous effects of extended task practice we found in behavioral studies of data entry (Healy et al., 2004). Rather, the model predicts that a decrease in either W or G would result in deterioration in both response time and accuracy. The simultaneous effects of W and G relate of course to the nature of the task being modeled. In the Sternberg task used by Jongman (1998) there are limited opportunities for learning, and the interaction of learning and fatigue could not be examined as well as in the extended repetitive task that we use in the present research (from Healy et al. (2004)).

More recently, considerable work on computational models of fatigue has been reported by Gunzelmann and colleagues (Gunzelmann, Byrne, Gluck, & Moore, 2009; Gunzelmann & Gluck, 2009; Gunzelmann, Gluck, Van

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