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Phases of learning: How skill acquisition impacts cognitive processing

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This fMRI study examines the changes in participants' information processing as they repeatedly solve the same mathematical problem. We show that the majority of practice-related speedup is produced by discrete changes in cognitive processing. Because the points at which these changes take place vary from problem to problem, and the underlying information processing steps vary in duration, the existence of such discrete changes can be hard to detect. Using two converging approaches, we establish the existence of three *learning phases*. When solving a problem in one of these learning phases, participants can go through three *cognitive stages*: Encoding, Solving, and Responding. Each cognitive stage is associated with a unique brain signature. Using a bottom-up approach combining multi-voxel pattern analysis and hidden semi-Markov modeling, we identify the duration of that stage on any particular trial from participants brain activation patterns. For our top-down approach we developed an ACT-R model of these cognitive stages and simulated how they change over the course of learning. The Solving stage of the first learning phase is long and involves a sequence of arithmetic computations. Participants transition to the second learning phase when they can retrieve the answer, thereby drastically reducing the duration of the Solving stage. With continued practice, participants then transition to the third learning phase when they recognize the problem as a single unit and produce the answer as an automatic response. The duration of this third learning phase is dominated by the Responding stage.

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1. Introduction

Across domains, practice is acknowledged to have transformative effects on performance. Several models of skill acquisition propose different explanations for how practice reduces the duration and increases the accuracy of task performance. These models differ in whether they attribute speedup either to discrete changes in the cognitive processes executed to solve a problem or to a greater efficiency of the same processes. In this paper, we address both explanations within the context of modeling the speed up in mathematical problem solving. In particular, we combine cognitive modeling with new methods of analyzing fMRI data to understand the detailed changes that take place as participants transition from the first time they solve a novel problem, to the point at which they automatically recognize a problem's solution.

1.1. Models of skill acquisition and practice related speedup

As people practice solving a problem, the time it takes to solve that problem decreases. Previous research has focused on understanding the nature of this speed up. In their classic paper, Newell and Rosenbloom (1981) observed that performance tends to speed up as a power function of the amount practice, highlighting what has been called the 'Power Law of Practice'. In their paper describing these effects, performance improvements were explained as chunking of cognitive processes into fewer processes (Newell & Rosenbloom, 1981). Subsequent research has refined this characterization of practice by investigating whether the speedup is really best fit as a power function (e.g. Heathcote, Brown, & Mewhort, 2000), and by examining to what degree the speedup might reflect changes in the strategies used for solving the problems (e.g. Delaney, Reder, Staszewski, & Ritter, 1998).

Unlike Newell and Rosenbloom's work, the Race model, which is part of the Instance Theory (Compton & Logan, 1991; Logan, 1988, 2002), described the learning mechanism for practice-related speedup as involving a quick shift from computation to retrieval followed by a power-like speed up in the retrieval. According to the Race model, each time a problem is practiced it becomes encoded in memory; then, when a participant sees the problem again, each of the previously encoded instances independently races to generate the response and the fastest process 'wins the race'. As the number of instances in which a participant retrieves the answer increases, the speed of the winning retrieval will increase as well. This model not only predicts a power-law speedup with practice, but also a decrease in the variability in latency with practice.

In contrast to the Race model, a number of studies have suggested the computation process may have its own speedup before the shift to retrieval. Delaney et al. (1998) argued that both computation and retrieval are strategies that have their own power-law speedup. Rickard's Component Power Law (CMPL) model (Bajic, Kwak, & Rickard, 2011; Bajic & Rickard, 2009; Rickard, 1997) focuses on two sources of speedup—the discrete switch from computation to retrieval and the speed up within the computation and retrieval phases. Initially Rickard focused on speed up in retrieval but he has also suggested that faster associative retrieval may be responsible for speed up in the computations used to solve a problem.

Fitts and Posner (1967) were the first to propose a three-phase model of skill acquisition that consists of a cognitive phase, an associative phase, and an autonomous phase. Anderson (1982, 1987) later related this to an early version of a cognitive architecture, the ACT theory. He suggested that the transition from the cognitive to the associative phase reflected a transition from computation of the answers to declarative retrieval of learned answers, and that the transition to the autonomous phase was produced when retrieval was replaced by a production rule that directly produced the response to the stimulus.

The task in this paper is modeled within modern ACT-R theory (Anderson, 2007; Anderson et al., 2004). ACT-R models specify the full time course of processing that occurs while performing a task, from perceptual encoding through response generation, differentially leveraging specific functional modules over the course of a task. A significant advantage of modeling at this level of detail is that it allows us to relate a model of skill acquisition to changes in brain activation by identifying the major