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Research article

Fitting a model to behavior reveals what changes cognitively when under stress and with caffeine

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ABSTRACT

A human subject experiment was conducted to investigate caffeine's effect on appraisal and performance of a mental serial subtraction task. Serial subtraction performance data was collected from three treatment groups: placebo, 200, and 400 mg caffeine. The data were analyzed by caffeine treatment group and how subjects appraised the task (as challenging or threatening). A cognitive model of the serial subtraction task was developed. The model was fit to the individual human performance data using a parallel genetic algorithm (PGA). The best fitting parameters found by the PGA suggest how cognition changes due to caffeine and appraisal. Overall, the cognitive modeling and optimization results suggest that due to caffeine and task appraisal the speed of vocalization varies the most along with changes to declarative memory. This approach using a PGA provides a new method for computing how cognitive mechanisms change due to moderators or individual differences.

Introduction

How is cognition preformed? Cognitive architectures are an approach to answer this question (Anderson, 2007; Newell, 1990). How does cognition change with moderators such as stress? Cognitive architectures enable researchers to better understand and model human cognition, as well as extend such models to encompass cognition in stressful situations. Understanding human cognition under stress through cognitive architectures has importance implications for improving Soldier performance during modern asymmetric warfare operations (Morelli & Burton, 2009; Stetz et al., 2007). Stress is used to describe experiences that are challenging both emotionally and physiologically (Selye, 1956), as well as psychologically (Matthews, 2016). Today's network-centric battlefield environment is highly stressful and cognitively demanding. A better understanding of cognition while under stress can provide insight into how warfighters make decisions on the battlefield, especially under time-critical life-or-death situations (Kowalski-Trakofler, Vaught, & Scharf, 2003).

A large-scale computational approach is presented that begins to explore the question of how cognition changes with stress. This approach uses methods from physiological psychology, cognitive architectures, and parallel genetic algorithms. We are able to provide an initial answer to how cognition changes due to stress in a task commonly used to study stress and due to caffeine consumed as a potential modulator of stress.

First, the task (a serial subtraction task), the subjects, and model are described. Then the model of the task is detailed, followed by the experiment methodology, and the results and discussion of the human study. Next, how the model was fit to the human data by varying three parameters of a cognitive architecture is explained. How the parameters varied gives some indication of how performance was modified by stress and by caffeine. This approach has flaws and further opportunities are discussed.

This section overviews the basic experimental method. The task is introduced, then the model used to predict performance on the task is described, and finally the methodological approach is explained.

Serial subtraction task

The task used to study stress is the serial subtraction task. A brief summary of the task is shown in Fig. 1. Serial subtraction is part of the Trier Social Stressor Task (TSST), which starts with a public speaking task about an embarrassing real-life episode or interviewing for a job

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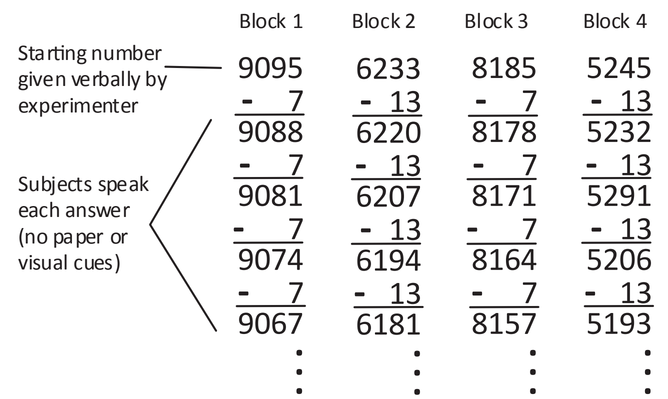

Fig. 1. An example of the serial subtraction task stimuli and the starting numbers for each block.

(Kirschbaum, Pirke, & Hellhammer, 1993). This task has been used hundreds of times in physiology studies to cause stress in subjects, which can then be measured in a variety of ways. The task is designed to cause psychosocial evaluative stress that results in physiological stress activation, and it does so routinely and reliably as measured by changes in heart rate, blood pressure, and stress hormone levels (e.g., Klein, Whetzel, Bennett, Ritter, & Granger, 2006; Kudielka, Hellhammer, Kirschbaum, Harmon-Jones, & Winkielman, 2007; Tomaka, Blascovich, Kelsey, & Leitten, 1993). Typically, the subjects' performance on the task is not recorded, and despite performance, all participants are told to improve their speed and accuracy. The task has solely been used to cause changes in physiology due to math anxiety and social comparison and has not been used to give insights about cognition and stress.

Before the task begins the experimenter explains that the subject's performance is going to be recorded and analyzed for accuracy (e.g., error type, percent correct, etc.). After the task is explained to the subject, a task appraisal questionnaire is completed, and the subject begins performing the task with no visual or paper clues. It is thought this anticipation period, for some subjects, increases anxiety and worry about poor performance on the upcoming task.

Subjects sit in a chair directly in front of and near the experimenter who is holding a time keeping device and clipboard of the correct subtraction answers that she checks off as the subject performs the task. Before the task begins the experimenter emphasizes the task should be performed as quickly and as accurately as possible. Often, and in our case, the experimenter wears a white lab coat to increase stress. The experimenter informs the subject of the starting number. From this point forward, the subject speaks the answer to each subtraction problem.

When an incorrect answer is given, the subject is directed to "Start over at < the last correct number > ". At two minutes into each four-minute session, subjects are told "two minutes remain, you need to go faster". This prompt enhances the time pressure component of the task. The next section describes the model developed to perform the serial subtraction task.

Modeling serial subtraction

A simple model of the serial subtraction task was developed to provide a description of how the task is performed, and contributes to a theory of how cognition and cognitive mechanisms change to give rise to performance. In the model, theory on mental arithmetic performance was combined with observations gathered during a previous serial subtraction study (Ritter, Bennett, & Klein, 2006) to create a cognitive model of the serial subtraction task.

The ACT-R cognitive architecture (Anderson, 2007) was chosen for several reasons: (1) it provides a symbolic structure in the form of a production system and a parameter-driven level of processing using a number of mathematical equations; (2) it permits the parallel execution of the verbal system with the control and memory systems; and (3) it has been used for other models of mathematical processing developed by other researchers (Anderson, 2005; Dehaene, Piazza, Pinel, & Cohen, 2003; Lebiere, 1999; Ravizza, Anderson, & Carter, 2008; Rosenberg-Lee, Lovett, & Anderson, 2009). According to Rosenberg-Lee et al. (2009), "The ACT-R cognitive architecture proposes that cognition is accomplished by the activity of independent modules that are co-ordinated by a production system. Modules represent various perceptual and motor modalities, such as vision and finger manipulation, and aspects of central cognition, such as retrieving memories, cognitive control, and the maintenance of internal representations." Fig. 2 shows the primary components of the ACT-R architecture. The dashed line represents the components used in the serial subtraction model.

The serial subtraction model performs a block of subtracting by 7 s or 13 s in a similar manner to that of the human subjects. The model's declarative knowledge consists of approximately 650 arithmetic facts and goal-related information. The model's procedural knowledge is made up of 24 production rules that allow for retrieval of subtraction and comparison facts necessary to produce an appropriate answer. The model performs subtractions using a column-by-column strategy. Table 1 shows several example arithmetic facts and a production rule used in the serial subtraction model. The declarative memory of the serial subtraction model is loaded with integer, addition, subtraction, multiplication, and comparison facts. A 'chunk-type' defines the structure for each type of fact. The top section of Table 1 shows example chunk types and several integer, addition and subtraction facts. The bottom section of the table shows an example production rule which is part of the borrowing operation when performing subtraction. If the fields in the top part of the production (above the = = > symbol) match the current state of the model's buffers, the production executes the lower statements (below the = = > symbol) which can modify the buffers.

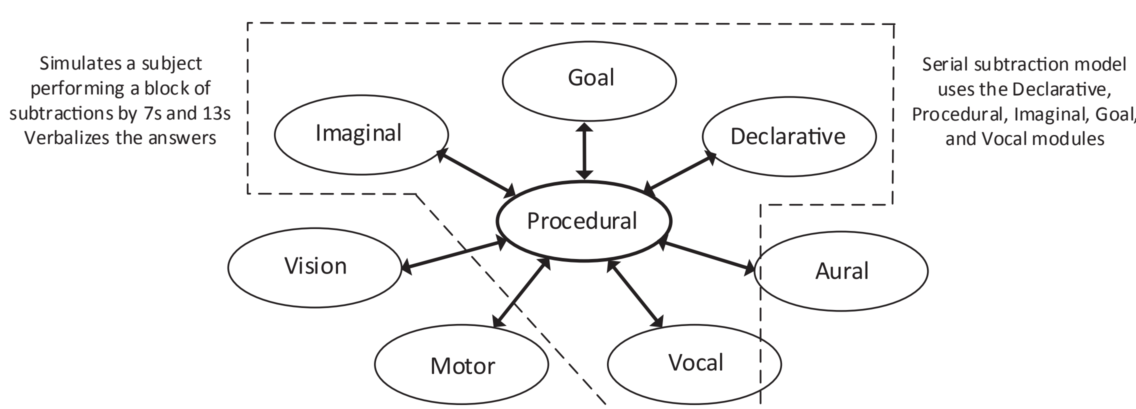

Fig. 2. The primary components of the ACT-R architecture. The components within the dashed line are used by the serial subtraction model.