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Action Selection and Human Error in Routine Procedures

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We discuss a computational process model of action selection in routine procedures. The model explains several types of human error—omissions, perseverations, and postcompletion error (PCE)—as natural consequences of its action selection mechanisms. Those mechanisms include associative spreading activation for prospective memory and explicit rehearsal strategies for retrospective memory. The model fits empirical data from multiple tasks and from multiple labs.

INTRODUCTION

Error is a common occurrence in everyday and in working life. Studying human error is important not only for what it reveals about the normal operation of cognitive mechanisms but also because with increasing capability and complexity of our technological systems (e.g., transportation, power generation) the amount of damage that can result from error is magnified. But studying human error is difficult because of the variability of error behavior. Furthermore, error often arises from the dynamic interactions of several cognitive processes that normally perform very reliably.

We have devised a unified framework which explains multiple types of human error—omissions, perseverations, and postcompletion error (PCE)—across multiple tasks with data collected from multiple labs. A unified framework is important because one cognitive system, i.e. the human mind, produces all error types. Obtaining the correct explanation for one error type then acts as a constraint for explaining other error types. Furthermore, if we are to predict error in complex task environments then multiple error types must fall naturally out of the theory.

Our model predicts error to occur according to the processes of the memory phase in which the model is acting, prospective and retrospective retrieval. The prospective memory phase uses a set of limited-capacity buffers to spread retrieval activation to long term memory according to associative priming. This is the model's mechanism of action selection. The model also possesses a retrospective retrieval phase for post-interruption resumption. For that phase is uses strategic goal strengthening (rehearsal) and functional decay.

REVIEW

Theories of Action Selection and Error

Working Memory Capacity. Patterns of error types constrain explanations of memory processes involved in action selection, and a few computational theories of memory have attempted to explain specific error types. Byrne and Bovair (Byrne & Bovair, 1997) explained postcompletion error as a function of limited-capacity working memory. They addressed high and low working memory demand as well as individuals' high and low working memory capacities. Their model assumed a hierarchical goal representational structure. This was based on a GOMS (Card, Moran, & Newell, 1983) analysis of an experiment task also reported in their study. Their CAPS model (Just & Carpenter, 1992) propagated activation necessary for retrieval of step representations downward from the task supergoal to subgoals to individual steps. Subgoals had to have their activations maintained above a certain threshold in order for them to remain accessible. Crucially, the main goal of the procedure would be satisfied before it was time to perform the postcompletion step. The presence of other information to maintain in an active state, in this case a three-back memory task, taxed the system to capacity such that it failed to maintain the postcompletion subgoal above threshold.

Memory for Goals. Another account of systematic error, Memory for Goals (Altmann & Trafton, 2002), posits that we encode episodic traces of our goals as we complete tasks. Each goal is encapsulated in an episodic memory, which sparsely represents a behavioral context at the time of its encoding. The strength of these memories decay over time such that it may be difficult to remember the correct point at which we resume a task after an interruption. Memory for Goals provides a process-level theory for why certain types of errors are made during a well-learned task as a consequence of retrospective, episodic memory (Altmann & Trafton, 2007; Ratwani & Trafton, 2010; Trafton, Altmann, & Ratwani, 2009). Memory for Goals implies that people are able to retrieve suspended goals successfully if and only if there are cues that prime them (Altmann & Trafton, 2002).

The Remember-Advance Model. Altmann et al. developed a formal model of their UNRAVEL sequence task, describing it as a two-phase retrieval process. The model carried over no task context from step to step in any sort of buffers or working memory. Instead, at the beginning of each step it retrieved an episodic encoding of the last action it performed. It then used that memory as the cue for an associative retrieval from long-term memory of the action to perform for the current step of the task. Perseverations occurred due to interference in the retrieval of the episodic codes during the first retrieval phase. Omissions were a consequence of associative interference during the prospective phase of retrieval.

ACT-R Process Model. We developed our computational process model using the ACT-R 6 cognitive architecture (Anderson, 2007; Anderson et al., 2004). ACT-R is a hybrid symbolic and subsymbolic computational cognitive architecture that takes as inputs knowledge (both procedural and declarative about how to do the task of interest) and a simulated environment in which to run. It posits several modules, each of which perform some aspect of cognition (e.g., long-term declarative memory, vision). Each module has a buffer into which it can place a symbolic representation that is made available to the other modules. ACT-R contains a variety of computational mechanisms and the ultimate output of the model is a time stamped series of behaviors including individual attention shifts, speech output, button presses, and the like. It can operate stochastically and so models may be non-deterministic.

Like the Remember-Advance Model, ours uses a two-phase retrieval process. Unlike the Remember-Advance Model, it only uses the retrospective phase for resumption of an interrupted task. Prospective retrieval is accomplished by storing a task state representation as the contents of a set of buffers as a working memory capacity. Associative activation spreading from those buffers to long-term declarative memory retrieves the next step in the sequence.

One of the benefits of embodying a theory in a computational architecture, such as ACT-R, is that it allows researchers to develop and test concrete, quantitative hypotheses and it forces the theorist to make virtually all assumptions explicit. To the extent that the model is able to simulate human-like performance the model provides a sufficiency proof of the theory. Furthermore, the constraints on model development imposed by the cognitive architecture are critical for building a cumulative science, an enterprise not traditionally one of cognitive science's strong suits (Anderson, 2002; Newell, 1973).

Interruptions

With the rapid rise of communication technologies that keep people accessible at all times, issues of interruptions and multitasking have become mainstream concerns. For example, Time magazine (Wallis, 2006) and the New York Times (Thompson, 2005) both reported stories about interruptions and multitasking and how they affect performance. The information technology research firm Basex issued a report on the economic impact of interruptions, which they estimated to be around $588 billion a year (Spira, 2005). Given the prevalence of interruptions, it is important to understand their implications for human performance.

Being interrupted greatly increases people's error rates (Trafton, Altmann, & Ratwani, 2011). After an interruption, people will frequently repeat a step that they have already performed or skip a step that needs to be performed. Sometimes these errors are irritating (e.g., ruining a meal by leaving out a crucial ingredient), but sometimes they can have disastrous consequences (e.g., taking medicine twice or not configuring the flaps for airplane takeoff). For these reasons we find the interruption paradigm to be both useful for eliciting error behavior from subjects in empirical studies as well as an important topic of study in its own right.

NEW CONTRIBUTION

Our model works by incorporating and coordinating two distinct systems underlying prospective and retrospective memory. Those systems are associative spreading activation (Anderson et al., 2004) and functional decay (Altmann, 2002), respectively.

Correct Behavior

Sequential tasks require prospective memory to remember what comes next and, when we resume after an interruption, retrospective memory to remember what was done last. Our model uses these two memory processes during these two behavioral phases, selecting the next step and remembering where it left off (Figure 1). Both processes are activation-based, though they differ in how they use memory activation.

Selecting the next step. Action selection is a prospective memory task, using a representation of the current task context to associatively prime retrieval of a memory representation of the next step. We use ACT-R's spreading activation mechanism to implement prospective memory. Furthermore, activation propagates from active buffer contents to long-term memory according to what we assume to be learned association from each context to its subsequent action (Botvinick & Plaut, 2004).

Resuming post-interruption. When people resume after having been interrupted, it is necessary to remember the last action performed and then to use that memory to continue task execution. Resumption trials, that is, those trials immediately following an interruption, require the retrospective retrieval of the last action performed. Our model constructs a sort of breadcrumb trail as it executes a sequential task. Upon completion of each step, the model creates a memory uniquely encoding that one instance of the trial event. Using ACT-R's concept of base level activation, that memory has high activation at the time that it is encoded. As time passes, that memory's strength decays and this decay serves a function. This allows old episodic memories to decay sufficiently so that they do not interfere with the retrieval of new memories. As the model continues task execution and time passes, newer episodic memories are encoded. Newer memories with strong activations keep getting stored in memory while old memories' activation strengths decay gradually until those memories can no longer be reliably retrieved. But decay occurs gradually so that relatively recent episodes still have some small chance of interfering with the most recently encoded episode.

When the model is interrupted, it immediately tries to remember the last action it executed, which is encoded in one of these episodes. The model tries to retrieve one of these breadcrumb memories. Retrieval provides a renewal of activation to the retrieved memory, effectively resetting its decay process. Because the model has limited capacity within

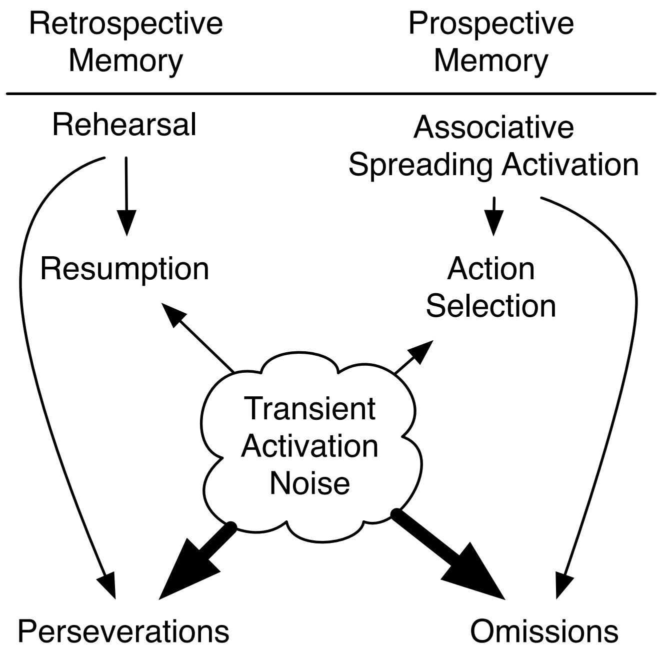

Figure 1. The role of noise in the model's memory processes: Associative spreading activation is the prospective memory process underlying selection of correct actions. When transient activation noise, a fundamental property of human memory, spikes during prospective retrieval it can lead to an omission. The model implemented retrospective memory with an explicit rehearsal strategy that it threaded with the interrupting task. Spikes in transient activation noise during retrospective retrieval sometimes caused perseverations.

its buffers, it must dedicate those buffers to the interrupting task. However, it can to some extent interleave operations for two separate tasks, in this case the interrupting task and rehearsal (Salvucci & Taatgen, 2008). Throughout the interruption, the model performs this threading of rehearsal with the interrupting task as an explicit rehearsal strategy. The model diverts just sufficient cognitive resources from the interrupting task to keep the episodic memory of the primary task active enough to provide a good chance of its retrieval at resumption.

The model uses rehearsal as a means to preserve reference to a particular piece of information across time. Each time it retrieves a memory, that memory's activation is strengthened (Altmann & Trafton, 2002; Anderson, 2007; Anderson et al., 2004). Meanwhile, other memories not used during rehearsal decay. This decay serves a function, which is to limit retrospective interference caused by other memories.

When people rehearse while doing something else, they are solving a problem imposed by the limited resources of their own cognition. They must preserve reference to some piece of information, but because of whatever task they are performing they have no place to put that information. However, if they interleave retrievals from long-term memory of that piece of information with their task performance, they can maintain a relatively high activation level for that piece of information while others that might cause interference are allowed to decay with the passage of time.

Salvucci and Taatgen (Salvucci & Taatgen, 2008) devised a theory of interleaved cognition that works well for this purpose, Threaded Cognition. By threading rehearsal, the model can maintain access to a memory despite its need to apply the limited resources of its buffers to the interrupting task. When the interrupting task ends, the model no longer requires its limited buffer resources be dedicated to that task, and so it can again put them to use on the main task. To resume, the model again retrieves its episodic memory. Having done so, it uses the reference to the action contained within the episodic memory—the last action performed—to start the next cycle of that task's execution.

Error Behavior

Errors arise out of the interaction of noise with the processes of normal task execution. Each of the two processes functions differently, and so the effects of their combinations with retrieval activation noise produces the two different sequence error types, omissions and perseverations.

Omission. We assume that association is somewhat imprecise in that there is not a clean one-to-one mapping of cue to target. Instead, some association "bleeds" over from the target to a handful of subsequent items, with each subsequent item receiving less association than the one coming before it in sequence. The model may omit a step when transient noise is such that it simultaneously suppresses activation of the correct next step and enhances activation of one of these subsequent items.

Furthermore, we assume that the model retains some representation of its task context in active buffers during its task execution. We assume, as Altmann and Trafton (Altmann & Trafton, 2007) have shown that people must rebuild such representations gradually at resumption. For the model this means that it has less retrieval activation available to spread for its first prospective retrieval attempt after the interruption. With the proportion of activation provided by noise larger in this case, the model is more likely than usual to retrieve the representation for an action that should come one or two more steps in the future.

Postcompletion Error. The model treats PCE as a special case of omission error. We assume that in tasks with a hierarchical goal structure, people retrieve a representation of the main task goal multiple times during the course of executing that task once. As in rehearsal, each time a memory is retrieved its activation is strengthened a degree. If such a memory's activation is already strengthened by repeated retrievals and it happens to belong to the set of the next few steps, then it has both this base-level activation which has not yet had time to decay, and it also has associative spreading activations. These two sources of activation coming together in the one memory makes the model even more likely than in the case of typical omissions to retrieve the memory of the main goal rather than the memory of the postcompletion step. This is why postcompletion steps, when present, elicit greater rates of omissions than do other steps.

Perseveration. The most recently performed step has the highest base-level activation because it was referenced most recently. However, the next most recently referenced step still has a high, albeit less so, base-level activation level. Noise can temporarily make the next-most-recently performed step more active than the most recently performed step. Typically this happens at interruption onset, when the model begins its rehearsal. It then rehearses an incorrect, but near action, i.e. from one or two steps back.

Empirical Studies

What follows is an accounting of the tasks with which we have developed our model and the theoretical contributions we have derived from each.

The Stock Trader Task. Our model performed a version of Ratwani and Trafton's (Ratwani & Trafton, 2011) stock trader task. This is a type of form-filling task wherein participants, using a graphical user interface, click a series of buttons in a specific order. The goal of the task is to fill out an order form according to information available within the display. An arithmetic task occasionally interrupted the financial management task for 15 seconds at a time.

The final step of the task consisted of a single button not placed within a box and placed above the right column of boxes. This arrangement broke with the Western reading convention followed by the progression of all of the other steps. This step was arranged this way because we intended it to serve as a postcompletion step. For modeling purposes the important points about the stock trader task were:

- It featured a primary task that was occasionally interrupted by a secondary task,
- Participants had to follow a specific procedure,
- The spatial layout of the interface (working from top to bottom down the left column and then the right column of) and the operations required to perform the task were quite intuitive,
- After entering information in each module, the participant clicked the Complete Order button (upper right corner). Clicking the Complete Order button was the postcompletion step and failing to click the Complete Order button constituted a PCE,
- The spatial layout of the task grouped steps by proximity. This encouraged use of an intuitive heuristic ("go down the column"), as well as having an isolated "clean-up" step at the end. This format followed the form of other tasks shown by GOMS analysis to lead to subgoaling (e.g., Byrne & Bovair, 1997),
- No information remained on the interface after clicking the confirm button within each module, i.e. no global place keeping (Gray, 2002).

The model retrieved each subsequent step using the prospective memory process described above. Additionally, we assume that in hierarchically-organized tasks such as this that people retrieve the main goal of the task as they traverse a goal hierarchy, prior to retrieving each subgoal. As each retrieval of a memory strengthens its activation, the main goal's activation does not decay during task execution. Rather it remains active enough to interfere with retrieval operations. Functionally-isolated steps like the postcompletion step both immediately follow and precede retrieval of the main goal, and so such steps are subject to much greater degrees of interference. Furthermore, at resumption the interference effect is exacerbated by the context representation's degraded ability to spread retrieval activation.

The Phaser Task. We applied our model to Byrne and Bovair's (1997) postcompletion phaser task from their second experiment. For our purposes the important points about that task were:

- Working memory load varied on a within-subjects basis, implemented by a three-item memory task,
- Participants varied in their own working memory capacities. Byrne and Bovair treated this as a two-level factor, split on the median,
- Participants had to follow a specific procedure.
- The spatial layout of the task grouped steps by proximity. This encouraged use of an intuitive heuristic ("do all the items in the cluster"), as well as having an isolated "clean-up" step at the end. Byrne and Bovair's own GOMS analysis of their phaser task resulted in a hierarchical task representation that they used in their CAPS model.

Occupying buffer space with an additional memory task or by adjusting a parameter related to individual differences in working memory capacity had the same effect on prospective retrievals as the interruption-resumption process. It restricted the amount of retrieval spreading activation available to the prospective retrieval process. This is why the model's PCE rate varied according to working memory load and working memory capacity, following the pattern observed in subjects.

The UNRAVEL Task. The UNRAVEL task (Altmann, Trafton, & Hambrick, 2014) is a sequential memory task in which subjects perform a two-choice decision regarding features of a simple alphanumeric display. UNRAVEL is an acronym for the stimuli features subjects responded to, such as that one item is <u>U</u>nderlined or italicized, the letter is <u>N</u>ear to or far from the beginning of the alphabet, etc. It is in several ways an ideal tool for studying sequential memory behavior because:

- Subjects must adhere to the prescribed sequence,
- Each decision has only two options,
- Each of the fourteen potential responses is indicated by a unique letter of the alphabet so that intended but incorrect actions are easily inferred,
- The interface provides no cues that may aid subjects' recall of their current position within the task sequence,
- It is well-suited to frequent interruptions,
- It has a flat goal structure, making it well-suited to studying repetitive tasks.

From the UNRAVEL task we were able to constrain the model's retrieval processes to account for the patterns of perseverations and omissions for both non-interrupted and interrupted trials. For the non-interrupted trials, the model's prospective memory processes accounted for subjects' virtually complete lack of perseverations and their 1% rate of omissions. For interrupted trials, the model's rehearsal strategy replicated subjects' 5.5% rate of perseverating 1-back (that is, repeating the last action), with decreasing rates for 2-back and 3-back, respectively. The model's degraded context representation at resumption explained subjects' 3% rate of 1-forward omissions (that is, skipping a single step), with slightly lower rates of 2- and 3-forward omissions, respectively.

DISCUSSION

The handful of processes comprising the process model, interacting dynamically, are sufficient to explain omissions, PCE, and perseverations. We speculate that the particular juxtaposition explaining PCE will also explain omissions particular to other functionally isolated procedure steps.

Comparison with Remember-Advance

The Remember-Advance model claims that for normal task execution people perform the same two-phase retrieval that they use for resumption. This means that for each step people must recall what they did last step. The implication here is that people do not retain a current task context representation in any sort of working memory-like buffer.

The process model somewhat simplifies assumptions underlying task execution relative to the Remember-Advance model. The process model uses two-phase retrieval sparingly because, time-wise, it is expensive, and even small-scale time costs matter (Gray & Boehm-Davis, 2000). Instead, for normal task execution it is a simpler explanation and provides for more efficient task execution for the model to retain some task context representation in an available working memory capacity, a buffer. This arrangement is congruent with the body of research supporting ACT-R, including Gray and Boehm-Davis' finding that milliseconds matter.

Explicit Rehearsal Strategies

The process model incurs the expense of rehearsal because of a necessity brought about by two factors: 1) it must persist state information over a longer duration than what decay would allow, and 2) it does not have the working memory capacity to retain this information and simultaneously accomplish its interrupting task. One solution is to at interruption onset pack away task state information into a form that can be retrieved later (an episodic memory), use just a little bit of cognitive resources to rehearse throughout the interruption, and at resumption attempt to retrieve that episode and then use it to reload the task context information to the active buffers.

Interruption duration impacts resumption performance because with every rehearsal iteration, there is a chance that an incorrect episodic memory could be retrieved. By ACT-R's base-level learning mechanism, every time a memory is retrieved, its activation is strengthened. Typically this manifested in the model's behavior when the model would, at rehearsal onset, retrieve by mistake an episodic memory from one or two trials ago rather than from the just-completed trial. Although this would often lead to the model rehearsing the wrong memory from the outset, a mistaken rehearsal later on could also lead to error.

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