# Memory Processes of Sequential Action Selection

**Franklin P. Tamborello, II (franklin.tamborello.ctr@nrl.navy.mil)**
National Research Council Postdoctoral Research Associate
Washington, DC, USA

**J. Gregory Trafton (greg.trafton@nrl.navy.mil)**
U. S. Naval Research Laboratory, 4555 Overlook Ave SW
Washington, DC 20032 USA

**Erik M. Altmann (ema@msu.edu)**
Michigan State University, 316 Physics Rd, Rm 298A
East Lansing, MI 48824 USA

## Abstract

We have devised a unified framework with which we can make predictions about several types of human error—omissions, perseverations, and PCE—across multiple tasks with data collected from multiple labs. Previously we have demonstrated this model for PCE from two tasks (Tamborello & Trafton, 2013). Now we demonstrate it for omissions and perseverations in Altmann, Trafton and Hambrick's (Altmann, Trafton, & Hambrick, 2014) UNRAVEL task.

**Keywords:** memory; architecture; cognitive model; action selection; error

## 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. This model mainly draws upon two previous works, the working memory hypothesis of Byrne and Bovair (Byrne & Bovair, 1997) and Memory for Goals (Altmann & Trafton, 2002).

Our model predicts error to occur as a combination of a limited-capacity to spread activation from working memory to long term memory as well as goal decay. Previously we have demonstrated this model for PCE from two tasks (Tamborello & Trafton, 2013). Now we demonstrate it for omissions and perseverations in Altmann, Trafton, and Hambrick's (2014, 2015) UNRAVEL task.

The UNRAVEL task 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 must respond to, such as that one item is Underlined or italicized, the letter is Near to or far from the beginning of the alphabet, etc. It is in several ways an ideal tool for studying sequential 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 that sequence,
- It is well-suited to frequent interruptions.

### Interruptions

The context we focus on is post-interruption resumption of a task. 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, building systems that can help remind an individual what they were doing or where they were in a task can have a large impact on productivity.

Being interrupted also greatly increases the number of errors (Trafton, Altmann, & Ratwani, 2011). People will frequently repeat a step that has already been performed or skip a step that needs to be performed after an interruption. 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).

## 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 the UNRAVEL 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).

# The UNRAVEL Task

## Method

**Participants** Three hundred Michigan State University undergraduates participated for credit toward course requirements or payment of $10. Participants were randomly assigned to one of three interruption duration conditions.

**Design and Materials** Figure 1 illustrates two example stimuli from the UNRAVEL task. Stimuli always consisted of one letter and one numeral, always with one inside a box in the center of the display and the other either above or below, one item was always either italicized or underlined, and one item in red or yellow. Aside from those constraints, items were presented in random order.

**Procedure** The experiment presented a display such as in Figure 1. Subjects were to remember which step of the UNRAVEL sequence they were currently on and to respond to the stimulus appropriately. As soon as subjects pressed a key indicating one of the fourteen potential responses, the experiment advanced to the next trial.

The experiment did not indicate to subjects when they erred. Sequence errors were coded with respect to the previous step. For example, if steps U, R, and A were performed in succession, R would be a +1 sequence error, because N was skipped, but A would be correct, because A follows R in the UNRAVEL sequence.

Participants worked in one of three between-subjects conditions according to duration of the interruption: one, two, or three consecutive interruption task trials. On average, the interruptions lasted 13, 22, or 32 seconds,

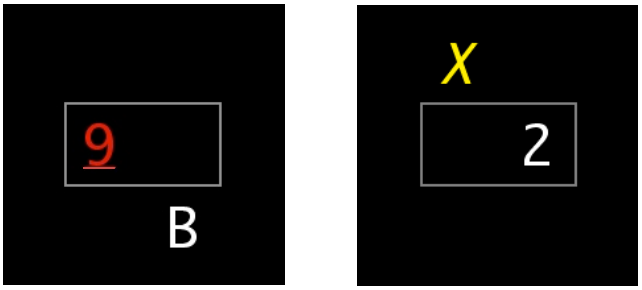


Figure 1. Left: The underlined numeral "9" is displayed in red in this example experiment display. Right: The italicized letter "X," is yellow in this example.

respectively, depending upon how quickly subjects completed the interrupting transcription typing task.

The experiment entailed 4 trial blocks with 10 interruptions each, averaging 6 trials between each interruption. Results appear together with the model results.

## Model

The 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

A task like UNRAVEL requires prospective memory to remember what comes next and retrospective memory to remember what was done last. Our model uses these two memory processes during the two phases of the UNRAVEL task, selecting the next step and remembering where it left off (Figure 2). Both processes are activation-based, though they differ in how they use memory activation.

**Selecting the next step** Most trials function using prospective memory to remember what step comes next. We assume that action selection is a prospective memory task. 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). During selection, the current step serves as a context which cues subsequent steps.

**Resuming post-interruption** With a task like UNRAVEL, wherein participants must 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 step of the UNRAVEL sequence that was performed. Of course, subjects in the UNRAVEL task are instructed to expect interruptions frequently.

Our model constructs a sort of breadcrumb trail as it executes the UNRAVEL 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 to unretrievability 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 UNRAVEL step 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 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.

By threading rehearsal (Salvucci & Taatgen, 2008), the model can maintain easy access to a memory despite its need to apply the limited resources of its buffers to the interruption 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 UNRAVEL task. To resume the UNRAVEL task, the model again retrieves its episodic memory. Having done so, it uses the reference to a step of UNRAVEL contained within the episodic memory—the last UNRAVEL step performed—to start the next cycle of that task's execution.

### Error Behavior

Errors arise out of the interaction of transient activation noise—an architectural feature of ACT-R—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

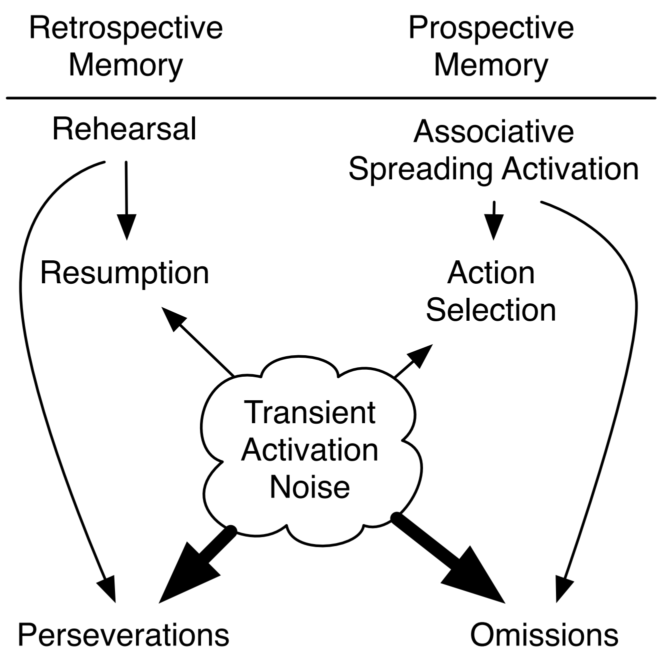


Figure 2. Associative spreading activation is the prospective memory process underlying selection of correct actions. When transient activation noise, a fundamental property of human memory, spikes during prospective retrieval it can lead to an omission. Likewise, the model implemented retrospective memory by an explicit rehearsal strategy that it threaded with the interrupting task. Spikes in transient activation noise during retrospective retrieval sometimes caused perseverations.

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 (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 relative amount of activation provided by noise larger in this case, the model is more likely than normally to retrieve the representation for an action that should come one or two more steps in the future.

**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).

### Model Results

We used our model to simulate data from 1,000 subjects. This large number of model runs allowed effects to converge on the model's true predictions. The model's means closely matched those of the participants, $R^2 = .87$, $F(1, 34) = 227$, $p < .001$. Figure 3 plots the model's means against the participants' means and 95% confidence intervals.

## Discussion

The combination of single-phase associative prospective retrieval for normal task execution and dual-phase functional decay retrospective retrieval with the prospective retrieval explained the pattern of omissions and perseverations quite nicely. Furthermore, because this is the same model we used to explain PCE in Byrne and Bovair's working memory capacity task and Ratwani et al.'s interruption task, it means that PCE is functionally identical to the omissions in this task with the exception that those steps happen to be functionally isolated within their tasks.

### Normal Task Execution

**Perseverations** Subjects appear not to have perseverated reliably during normal task execution. This is consistent with the process model's single-phase prospective retrieval mechanism for action selection.

**Omissions** UNRAVEL subjects exhibited at 1% rate of omission errors, even when the experiment did not interrupt them. Our process model explains this effect as a product of a relatively high ratio of associative spreading activation to retrieval noise during normal task execution. In this condition, the model operates with a representation of the current task context in two of its active buffers. These representations serve as the cues to prime associative retrieval. Two buffers supply more retrieval activation to the memory most associated to the current context than does one buffer alone.

### Interruption and Resumption

**Perseverations** The model uses decay to mitigate retrospective interference. However, decay takes time, and so the most recent one or two episodic codes may, with transient noise, have enough activation to interfere with the memory of the current task context. For this reason, the error-triggering interference tends to occur at the onset of rehearsal. The interruption occurs, the model retrieves an episodic code but because of interference that code is from one or two steps prior. Now that that older code has been strengthened by a retrieval instance it is the most active episodic code and so it is retrieved in each subsequent rehearsal cycle and at resumption.

**Omissions** For the process model, we assume that gradual rebuilding of task context representation (Altmann & Trafton, 2007) means that during resumption the model operates with less associative activation to spread than during normal task execution. The process model does this at resumption by copying the contents of the retrieved episode to only one of its active buffers. Then the model attempts prospective retrieval of the next step. However,

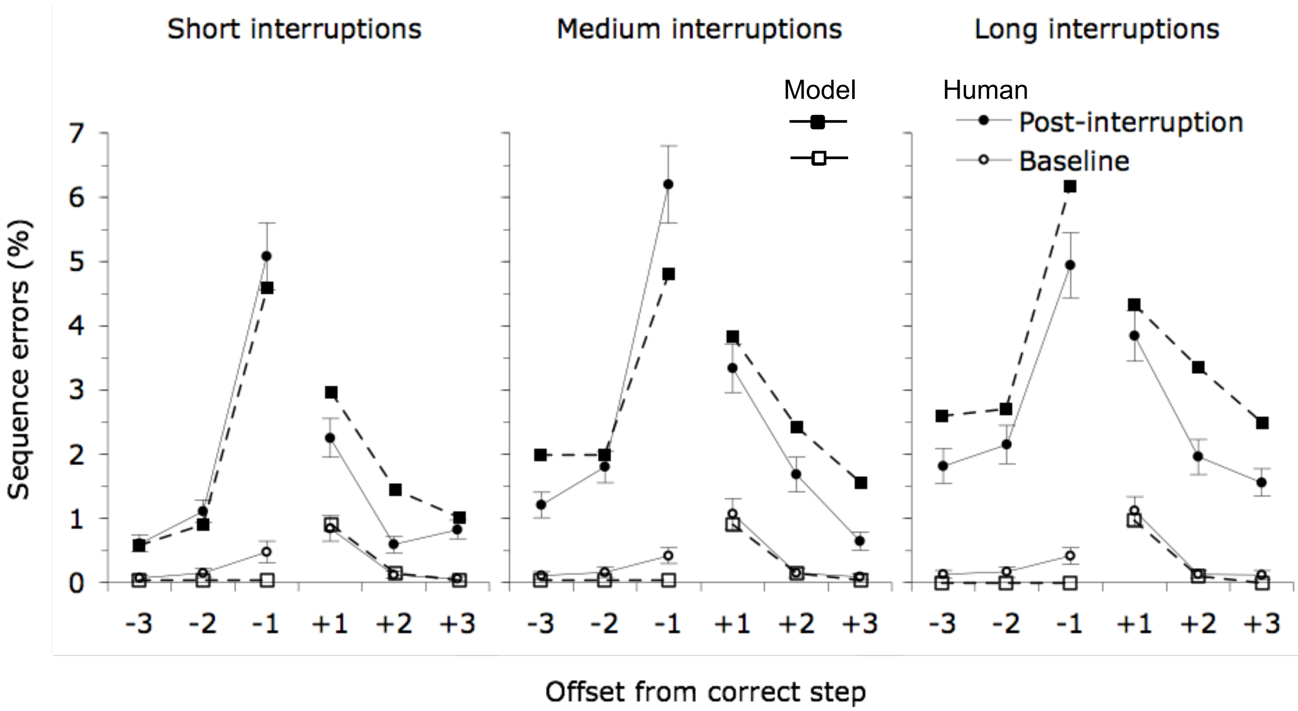


Figure 3. Human (solid lines, circle points) and model (dashed lines, square points) results for the UNRAVEL task. Error bars represent 95% confidence intervals for human data.

with only one buffer providing associative activation, the ratio of activation spreading to long-term memory versus noise is lower than it is during normal task execution. This means that spikes in noise are more likely to make other, slightly less-associated memories more active than the memory encoding the correct next step. When the model retrieves one of these other memories, it then omits the next correct step.

### 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. This arrangement is congruent with the body of research supporting ACT-R, including Gray and Boehm-Davis' finding that milliseconds matter.

### Explicit Rehearsal Strategies

But it incurs this expense 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 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 retrieve that episode and use it to reload the task context information to the active buffers.

Theories like ACT-R and Threaded Cognition are useful tools for exploring topics such as rehearsal in a busy task environment. With those two theories, we were able to constrain the space of possible rehearsal strategies to the one used by the model: immediate retrieval followed by subsequent retrievals at .52 second intervals.

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.

## References

Altmann, E. M. (2002). Functional decay of memory for tasks. *Psychol Res*, *66*(4), 287-97. doi:10.1007/s00426-002-0102-9

Altmann, E. M., & Trafton, J. G. (2002). Memory for goals: An activation-based model. *Cognitive Science*, *26*(1), 39-83. Retrieved from Google Scholar.

Altmann, E. M., & Trafton, J. G. (2007). Timecourse of recovery from task interruption: Data and a model. *Psychonomic Bulletin & Review*, *14*(6), 1079-1084.

Altmann, E. M., & Trafton, J. G. (2015). Brief lags in interrupted sequential performance: Evaluating a model and model evaluation method erik M. Altmann michigan state university. *International Journal of Human-Computer Studies.* Retrieved from Google Scholar.

Altmann, E. M., Trafton, J. G., & Hambrick, D. Z. (2014). Momentary interruptions can derail the train of thought. *J Exp Psychol Gen.* doi:10.1037/a0030986

Anderson, J. R. (2002). Spanning seven orders of magnitude: A challenge for cognitive modeling. *Cognitive Science*, *26*(1), 85-112. Retrieved from Google Scholar.

Anderson, J. R. (2007). *How can the human mind exist in the physical universe?* New York, NY: Oxford University Press. Retrieved from Google Scholar.

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), 1036-60. doi: 10.1037/0033-295X.111.4.1036

Botvinick, M., & Plaut, D. C. (2004). Doing without schema hierarchies: A recurrent connectionist approach to normal and impaired routine sequential action. *Psychol Rev*, *111*(2), 395-429. doi:10.1037/0033-295X.111.2.395

Byrne, M. D., & Bovair, S. (1997). A working memory model of a common procedural error. *Cognitive Science*, *21*(1), 31-61. Retrieved from Google Scholar.

Card, S. K., Moran, T. P., & Newell, A. (1983). *The psychology of human-computer interaction.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Freedman, M. L., & Martin, R. C. (2001). Dissociable components of short-term memory and their relation to long-term learning. *Cognitive Neuropsychology*, *18*(3), 193-226. doi:10.1080/02643290126002

Gray, W. D., & Boehm-Davis, D. A. (2000). Milliseconds matter: An introduction to microstrategies and to their use in describing and predicting interactive behavior. *Journal of Experimental Psychology: Applied, 6(4)*, 322-335. doi: 10.1037//1076-898X.6.4.322

Gunzelmann, G., Anderson, J. R., & Douglass, S. (2004). Orientation tasks with multiple views of space: Strategies and performance. *Spatial Cognition & Computation*, *4*(3), 207-253. Retrieved from Google Scholar.

Hanten, G., & Martin, R. C. (2000). Contributions of phonological and semantic short-term memory to sentence processing: Evidence from two cases of closed head injury in children. *Journal of Memory and Language*, *43*(2), 335-361. Retrieved from Google Scholar.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, *99*, 122-149. Retrieved from Google Scholar.

Martin, R. C., & Freedman, M. L. (2001). Short-term retention of lexical-semantic representations: Implications for speech production. *Memory (Hove, England)*, *9*(4-6), 261-80. doi:10.1080/09658210143000173

Miller, G. A. (1956). The magical number seven, plus or minus two. *Psychological Review*, *63*, 81-97.

Newell, A. (1973). You can't play 20 questions with nature and win: Projective comments on the papers of this symposium. In W. G. Chase (Ed.), *Visual information processing* (pp. 283-308). New York: Academic Press. Retrieved from Google Scholar.

Ratwani, R. M., & Trafton, J. (2010). A generalized model for predicting postcompletion errors. *Topics in Cognitive Science*, *2*(1), 154-167. doi:10.1111/j.1756-8765.2009.01070.x

Salvucci, D. D., & Taatgen, N. A. (2008). Threaded cognition: An integrated theory of concurrent multitasking. *Psychological Review*, *115*(1), 101-30. doi: 10.1037/0033-295X.115.1.101

Spira, J. B. (2005). The high cost of interruptions. *KM World*, *14*(8), 1. Retrieved from Google Scholar.

Tamborello, F. P., & Trafton, J. G. (2013). A long-term competitive process model of a common procedural error. In *Proceedings of the 35th annual conference of the cognitive science society.* Austin, TX: Cognitive Science Society.

Thompson, C. (2005). Meet the life hackers. *New York Times Magazine. URL: Http://www. Nytimes. Com/ 2005/10/16/magazine/16guru. Html (29th December 2011).* Retrieved from Google Scholar.

Trafton, J. G., Altmann, E. M., & Ratwani, R. M. (2009). A memory for goals model of sequence errors. In *Proc. 9th international conference of cognitive modeling.* Retrieved from Google Scholar.

Trafton, J. G., Altmann, E. M., & Ratwani, R. M. (2011). A memory for goals model of sequence errors. *Cognitive Systems Research*, *12*, 134-143.

Wallis, C. (2006). The multitasking generation. *Time Magazine*, *167*(13), 48-55. Retrieved from Google Scholar.