Effects of Memory Rehearsal on Driver Performance: Experiment and Theoretical Account

Dario D. Salvucci and **Joanna Beltowska,** Drexel University, Philadelphia, Pennsylvania

Objective: We report an experiment and a theoretical analysis concerning the effects of an exclusively cognitive task, specifically a memory rehearsal task, on driver performance. **Background:** Although recent work on driver distraction has elucidated the sometimes significant effects of cognitive processing on driver performance, these studies have typically mixed cognitive with perceptual and motor processing, making it difficult to isolate the effects of cognitive processing alone. **Method:** We asked participants to drive in a driving simulator during only the rehearsal stage of a serial-recall memory task while we measured their ability to maintain a central lane position and respond to the illumination of a lead vehicle's brake lights. **Results:** Memory rehearsal significantly affected drivers' steering performance as measured by lateral deviation from lane center, and it also significantly affected drivers' response time to the braking stimulus for the higher load memory task. **Conclusion:** These results lend support to a theoretical account of cognitive distraction provided by threaded cognition theory in terms of a cognitive bottleneck in procedural processing, and they also suggest that consideration of task urgency may be important in accounting for performance tradeoffs among concurrent tasks. **Application:** The experiment augments the current understanding of cognitive driver distraction and suggests that even exclusively cognitive secondary tasks may sometimes affect driver performance.

INTRODUCTION

Multitasking – performing two or more tasks together – arises in a wide variety of task domains, and one domain in particular that has garnered great interest is that of driving and driver distraction. Driver distraction has received attention from researchers as a fascinating and complex example of human multitasking as well as attention from the general media as an example of people's increasingly technological lifestyles and the safety implications thereof.

Much of the recent research on driver distraction has focused on the use of cellular telephones while driving, examining the effects of both phone dialing (e.g., Alm & Nilsson, 1994; Brookhuis, De Vries, & de Waard, 1991; Reed & Green, 1999) and conversations (e.g., McKnight & McKnight, 1993; Strayer & Drews, 2004; Strayer & Johnston, 2001) on driver performance. Related research has investigated the distraction potential of other in-vehicle devices, such as radios (e.g., Sodhi, Reimer, & Llamazares, 2002), e-mail systems (e.g., J. D. Lee, Caven, Haake, & Brown, 2001), and navigation devices (e.g., J. Lee, Forlizzi, & Hudson, 2008; Tsimhoni, Smith, & Green, 2004).

Perhaps not surprisingly, tasks that involve significant visual-manual interaction with an in-vehicle device, most notably cell phone dialing, as cited previously, tend to result in adverse effects on driver performance. Nevertheless, eliminating visual and/or motor demands from a task does not necessarily eliminate the task's effects on driving; numerous studies have noted that the cognitive demands of in-vehicle interaction can also result in effects on driver performance, albeit typically smaller effects than those arising from visual-manual interaction.

For instance, Alm and Nilsson (1995) found that a memory-span task affected drivers' ability to brake in response to a lead vehicle maneuver; J. D. Lee et al. (2001) reported a 30% increase in brake response time during use of a speech-based e-mail system; Levy, Pashler, and Boer (2006)

Address correspondence to Dario Salvucci, Department of Computer Science, Drexel University, 3141 Chestnut St., Philadelphia, PA 19104; salvucci@cs.drexel.edu. *HUMAN FACTORS,* Vol. 50, No. 5, October 2008, pp. 834–844. DOI 10.1518/001872008X354200.

found an effect of a concurrent choice task on brake response time; Horrey and Wickens (2004) reported a significant effect on lane deviation during voice dialing of a memorized phone number; and Strayer and Johnston (2001) found that unconstrained conversations resulted in a large increase in failures to detect traffic signals. In these and other studies, it has become clear that the cognitive aspects of in-vehicle interaction play a significant role in driver distraction and must be considered along with the more salient visual and motor aspects of interaction.

In this paper we consider the question of whether an exclusively cognitive task, specifically the mental rehearsal of a memorized list, can result in driver distraction. The studies outlined so far all involved some amount of perceptual and motor behavior while driving, both for perceiving stimuli (e.g., listening to sentence stimuli or experimenter instructions) and for producing responses (e.g., speaking a recalled list or conversational utterances). As such, the effects of perceptual-motor interaction, whether large or small, spill over into the cognitive aspects of interaction and make it difficult to isolate the cognitive components (e.g., possible effects of speech production during conversation).

To separate out the cognitive aspects of an in-vehicle task, we ran an experiment in which participants rehearsed a memorized list while driving in a driving simulator. Specifically, we asked participants to perform three tasks: a serial memory task in which a list of items is encoded, rehearsed, and finally recalled; a simple, simulated driving task, performed only during the rehearsal stage of the memory task; and a braking task in which participants tapped the brake in response to a lead vehicle's brake lights, also performed only during memory rehearsal. In terms of real-world situations, we imagined this combination of tasks as being roughly akin to a driver rehearsing a memorized list of errands to run or groceries to buy while navigating a typical roadway. Notably, the tasks isolated the effects of memory rehearsal on the driving and braking tasks, testing specifically whether rehearsal alone significantly affected performance.

To provide theoretical guidance for our work, we will discuss the empirical results in the context of a recently proposed theory of human multitasking called *threaded cognition* (Salvucci & Taatgen, 2008). Threaded cognition posits that multitasking behavior can be characterized as a combination of parallel and sequential processes: Whereas multiple resources (for perception, motor movement, memory, etc.) can operate in parallel to serve multiple tasks, a central procedural resource can operate only serially, on one task at a time, thus resulting in a central bottleneck on cognitive processing. The theory attempts to extend existing theories that incorporate multiple resources (e.g., Wickens, 1984, 2002) by specifying the precise procedural steps involved in individual tasks and how they interleave to produce concurrent multitasking behavior. The theory has interesting implications for driver distraction, and particularly distraction from an exclusively cognitive task, and these implications are the focus of the present effort.

We begin with a brief outline of threaded cognition theory and its predictions concerning memory rehearsal while driving. We then describe the experimental method and results and subsequently use these results to identify a potential issue with the theory and a potential solution that addresses this issue. In the final discussion, we aim to place both the empirical and theoretical results in a broader context, particularly with respect to their implications for real-world driving and driver distraction.

THREADED COGNITION AND INITIAL PREDICTIONS

Threaded cognition is a new theory and computational framework that aims to account for human multitasking behavior (Salvucci & Taatgen, 2008). The theory posits that cognition can maintain and execute multiple active task goals, resulting in concurrent "threads" of processing spread across a number of processing resources. Building on the larger framework of the ACT-R (adaptive control of thought-rational) cognitive architecture (Anderson et al., 2004), threaded cognition includes a central procedural resource as well as a variety of peripheral resources, including those for perceptual, motor, and memory processes (see also, e.g., Wickens, 2002). The procedural resource issues processing requests to and collects processing results from the other resources, and because this resource can process only serially, one task at a time, it serves as the central cognitive bottleneck in the theory. Each of the other resources can serve as its own bottleneck when one resource, such as declarative memory (Rohrer & Pashler, 2003), is needed for two or more concurrent tasks.

Threaded cognition defines how cognition interleaves the processing of multiple task goals on this central resource, favoring the least recently processed goals to achieve balanced execution of all goals. Previous work (Salvucci & Taatgen, 2008; see also Salvucci, 2001, 2005; Salvucci & Macuga, 2002) has explored how ACT-R and threaded cognition can account for the sometimes large effects of secondary task execution while driving, which are attributable to contention for visual resources – for instance, effects of cell phone dialing when visual guidance is required. For our focus here on cognitive distraction, it suffices to consider how the driving, memory rehearsal, and braking tasks utilize the central procedural resource and then consider how the two tasks share the resource under the tenets of the theory.

Driving in general involves a host of complex processes, ranging from lower-level vision to higher-level planning and navigation. For the present purpose, we focus exclusively on aspects of steering control (as needed for the experimental task described later) and, in particular, base our analysis on an ACT-R model of driving that has been validated for various aspects of driver behavior and performance (Salvucci, 2006). This model posits that steering control can be represented as a repetition of four procedural steps: (a) encode a near point of the roadway to determine lane center; (b) encode a far point of the roadway as a preview of upcoming curvature; (c) based on these two points, change steering angle according to a steering control law (Salvucci & Gray, 2004) and change accelerator or brake depression similarly (Salvucci, 2006); and (d) finalize the iteration and repeat.

The processing steps for steering are graphically depicted in Figure 1a. Each procedural step requires 50 ms of processing, an estimate established over several decades of empirical validation of ACT-R and other cognitive architectures (e.g., Laird, Newell, & Rosenbloom, 1987; Meyer & Kieras, 1997). (Note that because perceptual and motor aspects of the model are posited to occur in parallel with the cognitive steps, they do not affect the subsequent analysis and are not discussed here.) In all, the four procedural steps result in a steering update – an incremental change of steering angle and accelerator/brake depression – every 200 ms in a single-task driving-only scenario.

Along with the lateral steering aspect of driving, we also consider a braking task in which the driver must respond to the illumination of the lead vehicle's brake lights by pressing the brake pedal. The model of the braking task, depicted in Figure 1b, is very straightforward: The first step detects the illumination (note that the model is continually fixating on the lead vehicle and thus the detection can be done immediately), and the second step initiates the motor program to tap the brake pedal.

The memory rehearsal model is inspired by the ACT-R model of serial memory developed by Anderson and Matessa (1997; see also Anderson, Bothell, Lebiere, & Matessa, 1998), which posits that repeated retrievals strengthen the activation of list items and thus facilitate later recall. Our rehearsal model, following this scheme, simply performs repeated retrievals of the list items, as shown in Figure 1c. For each retrieval, the procedural resource initiates the retrieval process on the declarative memory resource, as defined by the ACT-R theory, which in turn performs the actual retrieval that boosts that item's activation. The duration of each declarative retrieval depends on the current activation level of the retrieved chunk, but a typical retrieval would require tens to hundreds of milliseconds to complete. Note that while the declarative resource executes the retrieval, the procedural resource remains idle during retrieval in this single-task scenario, simply waiting for retrieval to terminate before issuing a subsequent retrieval request.

Given these representations of the three tasks, threaded cognition dictates how the tasks interleave on the procedural resource. In particular, the theory states that when both tasks are active, their procedural steps interleave such that the least recently processed task is allowed to proceed; more detailed justification of this scheme can be found in the full treatment (Salvucci & Taatgen, 2008), but its critical feature is that this interleaving alternates between procedural steps for concurrent tasks and ensures balanced execution among the tasks.

Figure 1d illustrates how the rehearsal and driving tasks would be interleaved under the guidance of threaded cognition. For rehearsal, the interleaving of driving steps occurs largely during declarative memory usage; thus, we expect minimal impact of driving on the rehearsal task. For driving, however, the interleaving of an occasional rehearsal step can have a serious impact: The steering

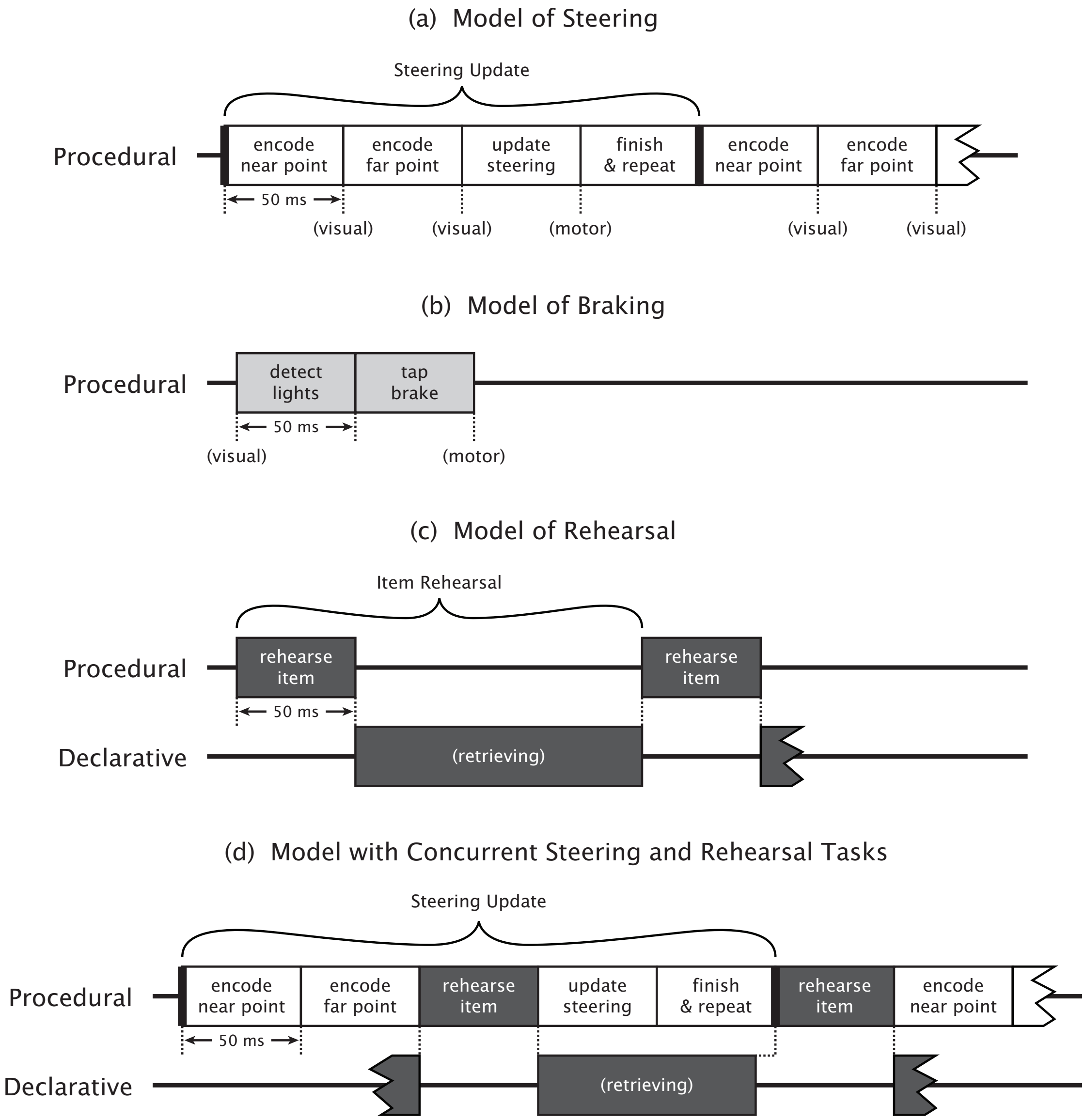

Figure 1. Graphical depictions of procedural resource and declarative-memory resource processing during (a) steering, (b) braking, (c) memory rehearsal, and (d) concurrent steering and rehearsal.

update time increases by roughly 50 to 100 ms – roughly a 25% to 50% slowdown of the 200-ms normal update latency – thus reducing steering accuracy with respect to the lane center. In addition, when the braking task is executed concurrently with driving and rehearsal, brake response may also be affected: If rehearsal steps intrude between the two steps of the brake model, brake response time is predicted to increase by 50 ms.

This initial analysis in the context of threaded cognition provides three predictions with respect to our experiment of memory rehearsal while driving:

1. The driving task should show a significant effect of memory rehearsal on steering accuracy, attributable to the slowdown in steering update frequency.
2. The braking task should show a significant effect of memory rehearsal on brake response time, with an effect size of roughly 50 ms corresponding to a single procedural step.
3. The rehearsal task should show no significant effect of the driving and braking tasks on recall performance because of the interleaving of these tasks in

the slack time between the rehearsal task's procedural steps.

The next section describes our experiment aimed at testing these initial predictions.

EXPERIMENT

In the experiment, participants performed a memory task that involved encoding a sequence of five or nine digits, rehearsing this sequence for a constant amount of time, and then recalling and typing the digits in order. The simulated driving task involved steering down a straight roadway in a driving simulator, the vehicle accelerating automatically from a full stop to highway speed; in addition, when the lead vehicle's brake lights were illuminated, drivers were asked to press the brake pedal as quickly as possible.

Experimental trials were distributed among four conditions: *drive-only,* which included only the driving task; *drive+rehearse5* and *drive+rehearse9,* in which participants memorized five- or nine-digit lists (respectively) and performed the driving task during the rehearsal stage only; and *rehearse9-only,* which included only the memory task with a nine-digit list. This design allowed us to investigate two potential effects of multitasking performance: the effects of rehearsal on steering and braking by comparing performance among the drive-only, drive+rehearse5, and drive+rehearse9 conditions; and the effects of driving on rehearsal by comparing recall performance between the rehearse9-only and drive+rehearse9 conditions.

Method

Participants. A total of 20 Drexel University students participated in the experiment for monetary compensation. The average age of participants was 24.3 years ($SD = 5.4$), and all participants had at least 2 years of licensed driving experience. One participant was excluded because of dropped data from a hardware problem; another participant was excluded because of extremely high single-task lateral deviations (more than two standard deviations from the mean), and to balance the analysis, we also excluded the participant with the lowest single-task deviation.

Materials. A schematic of the materials and procedure is shown in Figure 2. For the memory task, lists of digits 1 through 9 were randomly generated for each trial without replacement. For presentation, the screen was initialized with an underscore character at the position of each list item. Each digit then appeared in its respective position for 1 s and then disappeared (replaced by an underscore) as soon as the next digit appeared. Following the paradigm of Anderson and Matessa (1997), lists were presented in groupings of two or three digits, namely a 3-2 grouping for five-digit lists and a 3-3-3 grouping for nine-digit lists; the groupings were indicated by additional visual spacing between group boundaries. During recall, participants typed the digits in order with visual feedback of typed digits shown on the display.

For the simulated driving task, participants navigated the middle lane of a straight three-lane highway, with construction cones on both sides of the lane to encourage a central lane position. The simulation software, based on earlier versions of the software (Salvucci, 2005), handled the vehicle dynamics and graphics generation and interfaced with a Logitech steering wheel mounted on a desktop in front of a 20-inch (50.8-cm) display. (Note: The simulator incorporates a moderate amount of

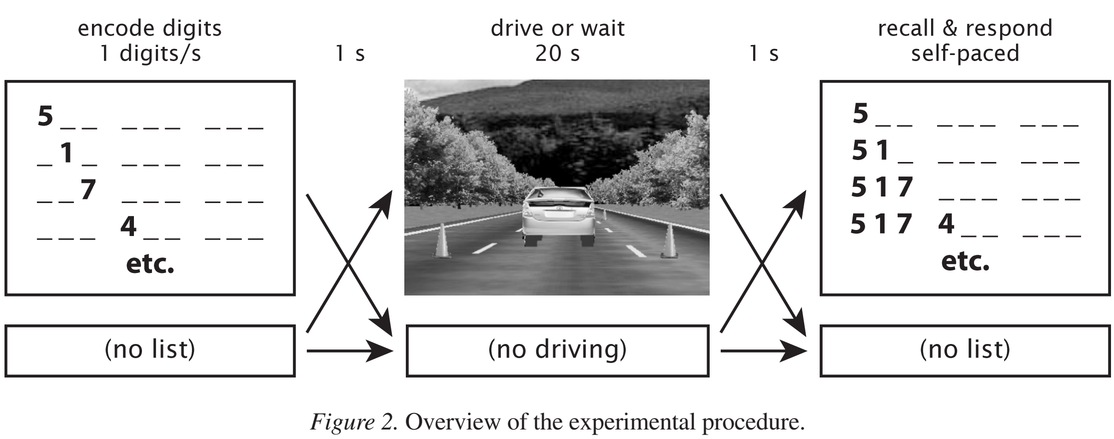

Figure 2. Overview of the experimental procedure.

noise in the vehicle dynamics: With a perfectly centered initial position and steering angle, the driver's vehicle moves with a root-mean-squared lateral error of 0.24 m from lane center; with 1° of steering angle displacement at 65 mph [105 kph], the vehicle moves 12 inches [30.5 cm] laterally in 1.0 s and 1 m laterally in 2.7 s.)

Each driving trial lasted 20 s and began with the driver's vehicle at a full stop. Immediately upon the start of the driving trial, the vehicle rapidly accelerated automatically (i.e., the driver did not control acceleration), reaching speeds of 51 mph (82 kph) after 5 s, 65 mph (105 kph) after 10 s, and finally 75 mph (120 kph) after 20 s.

The lead vehicle was maintained at a constant distance of 66 ft (20 m) in front of the driver's vehicle. Its brake lights were illuminated at a randomly chosen delay of 3, 6, 9, or 12 s after the start of the 20-s trial; the lights remained illuminated for 3 s or until the driver pressed the brake pedal. (Note that the lead vehicle's speed was not affected during illumination because of its constant distance from the driver's vehicle.) Participants were instructed to maintain a central lane position and to react as quickly as possible to the braking event.

Procedure. After 1 min of practice driving and one practice trial in each condition, participants completed 10 blocks of four trials, including one trial for each condition in randomized order. Each trial began with the presentation of the digit list to be memorized; in the drive-only condition, the message "no list" was instead displayed for 5 s. The screen then cleared for 1 s, followed by the start of a 20-s driving trial; in the rehearse9-only condition, which did not involve driving, the message "hands on wheel" was displayed for the 20-s period. Finally, participants typed the recalled list; in the drive-only condition, the message "no response needed" was displayed for 3 s.

Results

Driving performance. We measured driving performance in two ways: Steering performance was measured by lateral deviation of the vehicle from the lane center, and braking performance was measured by brake response time to the lead vehicle brake light stimulus. Lateral deviation was computed as the root-mean-squared error between the vehicle's lateral position and the center of the lane over the entire 20 s of each driving trial. Brake response time was computed as the average time between the illumination of the lead vehicle's brake lights and the first depression of the brake pedal. Brake response times more than two standard deviations from the participant's mean were removed as outliers because these data points represented behavior other than the required rapid brake response; this process removed less than 5% of the data points, within the acceptable range for outlier removal (Ratcliff, 1993). (Other methods of outlier removal, including the use of interquartile range and median, yielded the same significance results reported here.)

Figure 3 shows the mean lateral deviation in the three driving conditions. A repeated-measures ANOVA revealed a significant overall effect of condition on lateral deviation, $F(2, 32) = 4.03$, $p < .05$. There were pairwise differences between drive-only and drive+rehearse5, $t(16) = 2.38, p < .05$, and between drive-only and drive+rehearse9, $t(16) = 2.25, p < .05$, but no differences between drive+rehearse5 and drive+rehearse9, $t(16) < 1$. Thus, memory rehearsal significantly affected steering performance with respect to lateral deviation, and, moreover, the size of the effect did not depend on the difficulty of rehearsal as measured by list length.

Figure 4 shows the mean brake response time in the three driving conditions, and as for lateral deviation, there was a significant overall effect of condition on brake response time, $F(2, 32) = 5.48$, $p < .01$. Whereas there was no difference between the drive-only and drive+rehearse5 conditions, $t(16) < 1$, there were significant differences between drive-only and drive+rehearse9, $t(16) = 2.82, p < .05$, and between drive+rehearse5 and

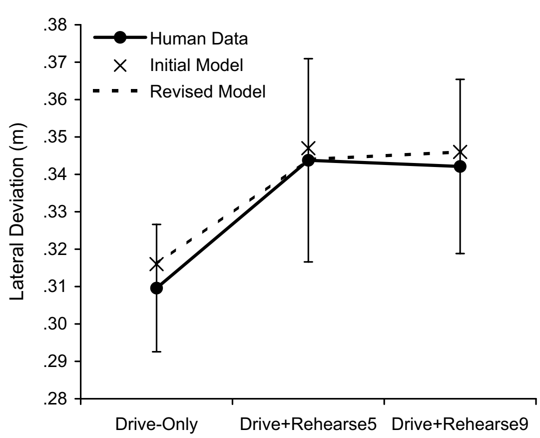

Figure 3. Lateral deviation by condition, data, and models. Error bars represent standard errors.

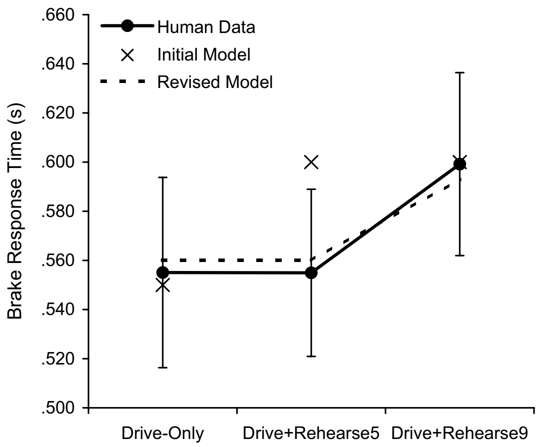

Figure 4. Brake response time by condition, data, and models. Error bars represent standard errors.

drive+rehearse9, $t(16) = 2.61, p < .05$. In other words, rehearsal of the shorter, five-item list did not increase brake response times, as compared with the baseline condition, but rehearsal of the longer, nine-item list did indeed result in increased brake response times with respect to baseline performance.

Recall performance. Performance on the rehearsal task can be measured as a function of recall performance in terms of total recall and response time, ratio of correctly recalled digits in their proper position, or number of correct digits before an incorrect response. In a comparison of the rehearse9-only and drive+rehearse9 conditions – the only difference being that drive+rehearse9 included driving during the 20-s rehearsal period – none of these measures showed significant effects of condition, $F(1, 16) < 1$ for all measures. For instance, mean recall accuracy (ratio of correct digits in proper position) was 73% in the drive+rehearse9 condition and 74% in the rehearse9-only condition; also, the mean number of correct digits before an incorrect response was 5.2 digits for both conditions. Thus, although memory rehearsal significantly affected driver performance, the driving task did not significantly affect the memory rehearsal task.

Comparing Results With Initial Predictions

This initial analysis in the context of threaded cognition provides three predictions with respect to our experiment on memory rehearsal while driving:

1. We correctly predicted that memory rehearsal would affect steering accuracy; the effect was statistically significant, albeit quite small in magnitude (0.03–0.04 m).
2. We obtained mixed predictions for the braking task: We correctly predicted an effect of rehearsal on brake response time of roughly 50 ms for the longer list (nine items) but incorrectly predicted that the effect would also hold for the shorter list (five items).
3. We correctly predicted that there would be no significant effect of driving on the rehearsal task as measured by recall performance.

Although the threaded cognition account yielded fairly good predictions overall, the incorrect prediction in Item 2 led us to analyze these tasks more deeply in order to better understand this subtle but important discrepancy between theory and data.

REVISITING THE PREDICTIONS AND THEORY

Our first step in revisiting our theoretical account involved developing and running computational model simulations based on the initial model presented earlier. In particular, we incorporated the model into the recently developed ACT-R driver model simulation engine (Distract-R: Salvucci, Zuber, Beregovaia, & Markley, 2005), and we modified the simulation such that the model experienced the same driving scenario as did the experiment participants. We varied the one model parameter that scales steering accuracy (see Salvucci, 2006) such that the model's baseline (driving-only) performance was near that of the human drivers (set at .81), and after locking this parameter, we estimated retrieval time for a list item as a free parameter to obtain the best fit to the human data (set at 90 ms). Motor time to press the brake pedal was left at the default value (400 ms: Salvucci & Taatgen, 2008).

The simulation results of the initial model are included in Figures 3 and 4. These results quantify the initial model's qualitative predictions – namely, that the initial model accounts for several important effects but fails to account for the brake response times in the drive+rehearse5 condition.

A closer look at the initial model's operation in Figure 5a reveals the core issue at hand in the model's inability to account for this data point. Between Points 1 and 2 in the figure, three tasks (steering, braking, and rehearsal) are being executed concurrently. Because all three tasks require the procedural resource during this time, threaded cognition equally divides resource processing

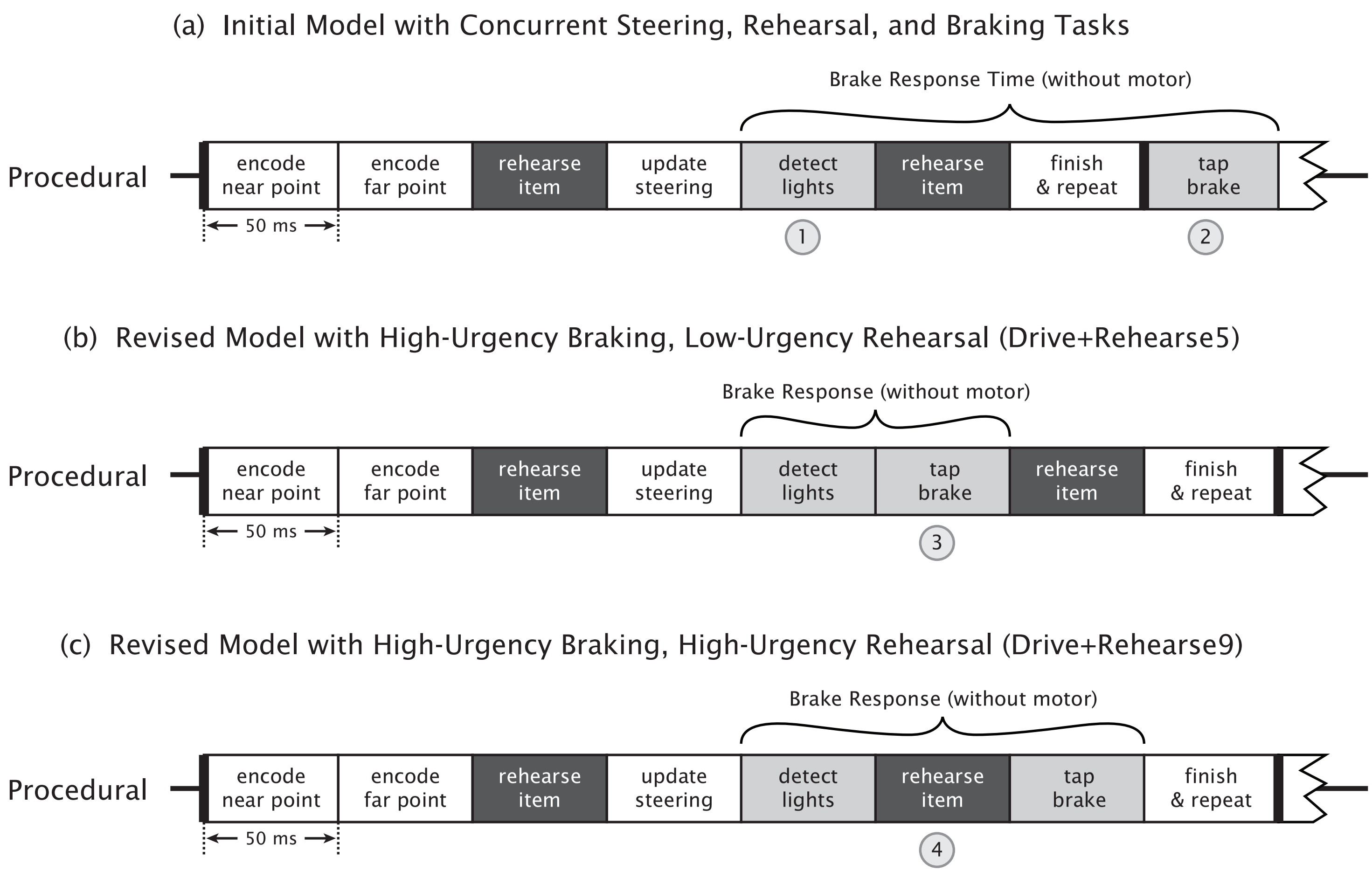

Figure 5. Graphical depictions of procedural resource processing during concurrent steering, rehearsal, and braking for (a) the initial model, (b) the revised model with low-urgency rehearsal, and (c) the revised model with high-urgency rehearsal.

among the tasks. For many concurrent task situations, this is, in our opinion, the common case and works well in accounting for people's ability to smoothly perform concurrent tasks.

In this particular case, however, there is a subtle distinction between the drive+rehearse5 and drive+rehearse9 conditions: for nine-item lists, people are working at capacity to maintain items during rehearsal, whereas for five-item lists, people can handle the rehearsal load fairly easily (as evidenced by a 98% recall accuracy in this condition). Thus, at the critical moment when all three tasks vie for the procedural resource, the drive+rehearse9 rehearsal task has a great deal more urgency than the drive+rehearse5 rehearsal task in needing to maintain its frequency of retrievals.

This observation led us to test a straightforward idea – namely, of considering cognitive threads as having either a high or low urgency and allowing threaded cognition to take urgency into account in its scheme for resource scheduling. (Note that a continuous value for urgency, rather than this binary value, would clearly be more general but was not needed in the present analysis.) We realized this idea by having threaded cognition prefer high-urgency tasks over low-urgency tasks, yet keeping with the theory's existing scheme within each category of urgency. For our experiment, we can consider the braking task as high urgency, the rehearsal task as high or low urgency for the drive+rehearse9 or drive+rehearse5 condition, respectively, and the steering task as low urgency. (Although steering is clearly more important than rehearsal for safety reasons, urgency represents the need for a particular procedural step to fire immediately, not necessarily the priority of the task in a larger sense.)

The processing timelines of this revised model with high- and low-urgency rehearsal are shown in Figure 5. For low-urgency rehearsal, in Figure 5b, the braking task is the only high-urgency task at Point 3 and thus is allowed to proceed on the procedural resource. Braking thus occurs as fast as possible, just as without rehearsal, thus resulting in the same brake response times between the drive-only and drive-rehearse5 conditions. In contrast, for high-urgency rehearsal, in Figure 5c, the braking and rehearsal tasks are both of high urgency, and thus a rehearsal step is interleaved between the braking steps. This extra step results in an extra 50-ms delay in brake response time in the drive-rehearse9 condition.

We reran the simulations using this revised model, and we slightly adjusted braking motor time for all conditions (set at 460 ms) to better fit the human data. The revised model results are included in Figures 3 and 4. The overall fit remains unchanged compared with the initial model, except that the consideration of low-urgency retrieval in the drive-rehearse5 condition now provides a better account for the brake response results. The effect size is close to, but slightly smaller than, the empirical effect size of 50 ms because a retrieval step does not always interleave with the braking task.

In fact, the human data provide further evidence of the importance of task urgency. We ran a correlation analysis on individual participants in the drive+rehearse9 condition to test whether increased recall performance (measured by the ratio of correct digits) led to decreased driving performance and vice versa. The analysis revealed no significant correlation between lateral deviation and recall performance, $R = .01$, but a significant correlation between brake response time and recall performance, $R = .43, p < .05$ (one-tailed); in other words, better recall performance correlated with slower brake response time, and as recall performance diminished, brake response times became faster. This result suggests a speed-accuracy trade-off in which some participants had a higher urgency for rehearsal and accepted slower brake responses as a result, whereas others had a lower urgency for rehearsal in order to make brake responses as fast as possible.

Overall, the revised model is in some ways only partially satisfying: We were able to account for the final incorrect prediction, but at the expense of proposing a subtle but fundamental rethinking of threaded cognition as incorporating a sense of urgency for individual tasks. Nevertheless, we believe that this rethinking could be a harbinger of a more significant shift in the theory. In fact, the idea is not even completely new for threaded cognition: A precursor framework (Salvucci, 2005) allowed for task goals to have desired initiation times that differ from the current time, thus allowing tasks to specify when they will require more processing (e.g., either immediately or sometime in the near future).

In addition, the theory's least recently used scheme for resolving resource conflicts can be couched in terms of urgency and initiation times, if one assumes that each rule's next step has a desired initiation time that equals the current time. The notion of urgency is also related to priorities and dual-task trade-offs that have been discussed in previous work (e.g., Navon & Gopher, 1997). Our current effort can be viewed as an important initial step in exploring the potential for urgency to become a necessary component of threaded cognition theory.

GENERAL DISCUSSION

In summary, our experiment revealed that even the exclusively cognitive task of memory rehearsal produced effects on driver performance with respect to both lateral deviation and brake response time. These results extend earlier findings (e.g., Alm & Nilsson, 1995; Horrey & Wickens, 2004; Strayer & Johnston, 2001) in that our experiment showed effects of cognitive distraction even when isolating the cognitive component of the secondary task. Threaded cognition accounted for almost all the effects in our initial account, but it required incorporation of task urgency to more fully account for the human data.

To understand the implications of this work for real-world driving, it is important to consider a few limitations of the work and how the results might generalize to realistic driver behavior. First, it should be noted that although the effects we have noted are statistically significant, they are fairly small in magnitude. For lateral deviation, the total effect size was approximately 0.03 to 0.04 m, as compared with a mean lateral deviation of 0.31 m found for driving alone; for comparison, in an experiment using the same driving simulator, manual dialing of a cell phone was found to increase lateral deviation by 0.14 m. In many situations, the small additional deviation resulting from memory rehearsal would likely not amount to any appreciable differences with respect to driver safety.

For brake response time, the total effect size was roughly 50 ms, during which a vehicle traveling 65 mph (105 kph) would travel roughly 4.75 ft (1.45 m). Again, in many situations, such a difference may not result in an unsafe situation; at the same time, one might imagine that this difference could present safety concerns in situations with high-velocity travel and tight traffic (e.g., a city highway during rush hour). In addition, the frequency with which drivers perform memory-related tasks at or above normal capacity limits (such as for the nine-item list) remains unclear. Nevertheless, the statistical significance of these effects indicates an interesting interaction between driving and the exclusively cognitive memory task.

Another important issue relates to the use of a driving simulator for the study of driver behavior. Driving simulators have long been used to study driver distraction because of their ease of use, lower costs, and reduced safety risks as compared with real-world driving. Some research efforts have collected both simulator and on-road data for similar tasks to gauge potential differences that may arise between these methods (e.g., Angell et al., 2006; Reed & Green, 1999; Santos, Merat, Mouta, Brookhuis, & de Waard, 2005); overall, the literature seems to suggest that simulator and on-road measures generally show the same basic effects, though they may differ with respect to the magnitude of the effects. The present work would certainly benefit from a follow-up experiment examining on-road performance, especially in conjunction with a secondary memory task couched in a real-world scenario (e.g., remembering a shopping list while driving to the store).

A third limitation of the present study involves the constraint that in this experiment, the vehicle accelerated automatically and the driver could not control speed. We decided on this constraint because we expected that when driving with a high memory load, as in our task with the nine-item list, drivers would reduce their speed to compensate for their potentially decreased attention to steering. Although the constraint facilitated our focus on lateral steering performance, it ignores the realistic trade-offs exhibited by drivers in real-world scenarios. Our theoretical account would predict that both lateral steering performance and longitudinal speed control would be affected by increased contention for the procedural resource by a secondary task, and we have observed and modeled such effects in previous efforts (Salvucci & Macuga, 2002).

Nevertheless, the theory does not address the important issue of how drivers balance their trade-offs between tasks, and it also has not yet accounted for how individual drivers may choose different points in the trade-off space for two tasks. Future empirical work that addresses these issues, along with new modeling approaches that account for them (e.g., Brumby, Howes, & Salvucci, 2007), will help in providing guidance for how the theory might be extended to account for these complexities in behavior.

ACKNOWLEDGMENTS

This work was supported by Office of Naval Research Grant N00014-03-1-0036 and National Science Foundation Grant IIS-0426674 to the first author. We thank Niels Taatgen, John Anderson, John Lee, and two anonymous reviewers for their many helpful comments and suggestions.

REFERENCES

Alm, H., & Nilsson, L. (1994). Changes in driver behaviour as a function of hands-free mobile phones – A simulator study. *Accident Analysis and Prevention, 26,* 441–451.

Alm, H., & Nilsson, L. (1995). The effects of a mobile telephone task on driver behaviour in a car following situation. *Accident Analysis and Prevention, 27,* 707–715.

Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of the mind. *Psychological Review, 111,* 1036–1060.

Anderson, J. R., Bothell, D., Lebiere, C., & Matessa, M. (1998). An integrated theory of list memory. *Journal of Memory and Language, 38,* 341–380.

Anderson, J. R., & Matessa, M. (1997). A production system theory of serial memory. *Psychological Review, 104,* 728–748.

Angell, L., Auflick, J., Austria, P. A., Kochar, D., Tijerina, L., Biever, W., et al. (2006). *Driver workload metrics project: Task 2 final report* (Tech. Rep. #DOT-HS-810-635). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.

Brookhuis, K. A., De Vries, G., & de Waard, D. (1991). The effects of mobile telephoning on driver performance. *Accident Analysis and Prevention, 23,* 309–316.

Brumby, D. P., Howes, A., & Salvucci, D. D. (2007). A cognitive constraint model of dual-task trade-offs in a highly dynamic driving task. In *Human factors in computing systems: CHI 2007 Conference proceedings* (pp. 233–242). New York: ACM Press.

Horrey, W. J., & Wickens, C. D. (2004). Driving and side task performance: The effects of display clutter, separation, and modality. *Human Factors, 46,* 611–624.

Laird, J. E., Newell, A., & Rosenbloom, P. S. (1987). Soar: An architecture for general intelligence. *Artificial Intelligence, 33,* 1–64.

Lee, J., Forlizzi, J., & Hudson, S. E. (2008). Iterative design of MOVE: A situationally appropriate vehicle navigation system. *International Journal of Human-Computer Studies, 66,* 198–215.

Lee, J. D., Caven, B., Haake, S., & Brown, T. L. (2001). Speech-based interaction with in-vehicle computers: The effect of speech-based e-mail on drivers' attention to the roadway. *Human Factors, 43,* 631–640.

Levy, J., Pashler, H., & Boer, E. (2006). Central interference in driving: Is there any stopping the psychological refractory period? *Psychological Science, 17,* 228–235.

McKnight, A. J., & McKnight, A. S. (1993). The effect of cellular phone use upon driver attention. *Accident Analysis and Prevention, 25,* 259–265.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review, 104,* 3–65.

Navon, D., & Gopher, D. (1997). On the economy of the human-processing system. *Psychological Review, 86,* 214–255.

Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychological Bulletin, 114,* 510–532.

Reed, M. P., & Green, P. A. (1999). Comparison of driver performance on-road and in a low-cost simulator using a concurrent telephone dialing task. *Ergonomics, 42,* 1015–1037.

Rohrer, D., & Pashler, H. E. (2003). Concurrent task effects on memory retrieval. *Psychonomic Bulletin and Review, 10,* 96–103.

Salvucci, D. D. (2001). Predicting the effects of in-car interface use on driver performance: An integrated model approach. *International Journal of Human-Computer Studies, 55,* 85–107.

Salvucci, D. D. (2005). A multitasking general executive for compound continuous tasks. *Cognitive Science, 29,* 457–492.

Salvucci, D. D. (2006). Modeling driver behavior in a cognitive architecture. *Human Factors, 48,* 362–380.

Salvucci, D. D., & Gray, R. (2004). A two-point visual control model of steering. *Perception, 33,* 1233–1248.

Salvucci, D. D., & Macuga, K. L. (2002). Predicting the effects of cellular-phone dialing on driver performance. *Cognitive Systems Research, 3,* 95–102.

Salvucci, D. D., & Taatgen, N. A. (2008). Threaded cognition: An integrated theory of concurrent multitasking. *Psychological Review, 115,* 101–130.

Salvucci, D. D., Zuber, M., Beregovaia, E., & Markley, D. (2005). Distract-R: Rapid prototyping and evaluation of in-vehicle interfaces. In *Human factors in computing systems: CHI 2005 Conference proceedings* (pp. 581–589). New York: ACM Press.

Santos, J., Merat, N., Mouta, S., Brookhuis, K., & de Waard, D. (2005). The interaction between driving and in-vehicle information systems: Comparison of results from laboratory, simulator and real-world studies. *Transportation Research Part F, 8,* 135–146.

Sodhi, M., Reimer, B., & Llamazares, I. (2002). Glance analysis of driver eye movements to evaluate distraction. *Behavior Research Methods, Instruments and Computing, 34,* 529–538.

Strayer, D. L., & Drews, F. A. (2004). Profiles in driver distraction: Effects of cell phone conversations on younger and older drivers. *Human Factors, 46,* 640–649.

Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological Science, 12,* 462–466.

Tsimhoni, O., Smith, D., & Green, P. (2004). Address entry while driving: Speech recognition versus a touch-screen keyboard. *Human Factors, 46,* 600–610.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman, J. Beatty, & R. Davies (Eds.), *Varieties of attention* (pp. 63–101). New York: Wiley.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science, 3,* 159–177.

Dario D. Salvucci is an associate professor of computer science at Drexel University. He received his Ph.D. in computer science from Carnegie Mellon University in 1999.

Joanna Beltowska is a Ph.D. student in computer science at Drexel University. She received an M.Sc. in media technology and engineering from Linkoping University in 2008.

Date received: April 10, 2008
Date accepted: October 4, 2008