Focus on Driving: How Cognitive Constraints Shape the Adaptation of Strategy when Dialing while Driving

Duncan P. Brumby
UCL Interaction Centre
University College London
London WC1E 6BT UK
Brumby@cs.ucl.ac.uk

Dario D. Salvucci
Department of Computer Science
Drexel University
Philadelphia PA 19104 USA
Salvucci@cs.drexel.edu

Andrew Howes
Manchester Business School
University of Manchester
Manchester M15 6PB UK
HowesA@manchester.ac.uk

ABSTRACT

We investigate how people adapt their strategy for interleaving multiple concurrent tasks to varying objectives. A study was conducted in which participants drove a simulated vehicle and occasionally dialed a telephone number on a mobile phone. Experimental instructions and feedback encouraged participants to focus on either driving or dialing. Results show that participants adapted their task interleaving strategies to meet the required task objective, but in a manner that was nonetheless intricately shaped by internal psychological constraints. In particular, participants tended to steer in between dialing chunks of digits even when extreme vehicle drift implied that more reactive strategies would have generated better lane keeping. To better understand why drivers interleaved tasks at chunk boundaries, a modeling analysis was conducted to derive performance predictions for a range of dialing strategies. The analysis supported the idea that interleaving at chunk boundaries efficiently traded the time given up to dialing with the maintenance of a central lane position. We discuss the implications of this work in terms of contributions to understanding how cognitive constraints shape strategy adaptations in dynamic multitask environments.

Author Keywords

Multitasking; User and Cognitive models; Handheld Devices and Mobile Computing; Transport.

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation] User Interfaces: Theory and methods; K.4.1 [Computers and Society] Public Policy Issues: Human safety; H.1.2 [Models and Principles] User/Machine Systems: Human factors.

INTRODUCTION

A safety critical task performed by millions of people around the world on a daily basis is driving an automobile. Indeed, there were some 250 million registered passenger vehicles in the U.S. alone in 2006 [21]. As mobile devices become ever entwined in supporting our daily activities, it is perhaps inevitable that these devices will be 'along for the ride' with the potential to distract the driver. Previous research has consistently demonstrated that interacting with a secondary in-car device can impair performance and increase the risk of a crash [1,10,17,18,19]. These effects can be attributed to the driver having to sequentially interleave attention between tasks over time [4,5].

One issue that has not been given sufficient attention is that people can potentially adopt different strategies for interleaving attention between driving and a secondary in-car task. Consider for a moment the classic example of manually dialing a telephone number while driving [1,17,19]. Here, the driver needs to look away from the road in order to dial and can choose to dial more or fewer digits at a time before looking back at the road. Presumably the choice of interleaving strategy will affect performance and impact safety [6,10]. At the same time there can be tight constraints imposed by prior knowledge and experience of how to perform a routine procedural task [7] that limit the range of available strategies. Telephone numbers for instance conform to specific representational conventions, such as the 3-3-4 grouping of digits common across the US. So for the dialing-while-driving example, the dialing task imposes internal psychological constraints that might limit the space of interleaving strategies that a driver might consider adopting. Given such limitations on strategic variability, we would expect an analysis of the driver's task objective to be critical to determining their behavior. The question of how objectives shape multitasking strategies is an important one for Human-Computer Interaction research given the field's promotion of mobile technologies: A better understanding will greatly facilitate the design, prototyping, and evaluation of such technologies in the context of how people actually use them in dynamic multitask contexts.

In this paper, we investigate how people adapt their strategy for interleaving multiple concurrent tasks to different objectives. We consider objectives in this context to be influenced by many factors—for instance, desired speed of performance or perceptions of risk. A study is described in which participants completed a dialing task while driving a simulated vehicle. Experimental instructions and feedback encouraged participants to focus on either driving or

CHI 2009, April 4–9, 2009, Boston, Massachusetts, USA.

dialing. The idea of the focus-on-driving condition was to capture something of the intent, if not the specific details, of public information campaigns aimed at improving safer driving behaviors. The focus on dialing condition acted as a control. We focus on the subtle adaptations of multitasking strategy to objective—in particular, how task interleaving is guided by the combination of psychological constraints on the retrieval of chunks associated with the dialing task while also being shaped by the desire to counter extreme vehicle drift. A computational modeling analysis is presented to better understand why drivers might favor a strategy that interleaves attentional resources at chunk boundaries over alternative strategies. The analysis suggests strategies are selected for efficiency, trading-off the amount of time allocated to dialing with the maintenance of a central lane position.

Background: Interleaving Multiple Tasks

It is generally understood that when people perform more than one task at a time, constraints on the human cognitive architecture [2,13] limit the extent to which multiple tasks can be performed in parallel. For instance, drivers might need to shift their attention away from the road to interact with a visually demanding secondary in-car device. This constraint on the field of effective vision forces the driver to make choices about which task to focus on at any moment; essentially, attention must be sequentially interleaved between tasks over time. How these basic task processes are ordered permits a range of multitasking strategies.

Brumby et al. [4,5] have utilized a modeling approach called Cognitive Constraint Modeling (CCM) [11] to explore systematically a range of plausible strategies for interleaving a simple phone dialing task with steering control. Various strategies were evaluated that dialed more or fewer digits at a time and gave more or less time to steering control. Analyses of this strategy space revealed a classic speed-accuracy trade-off in performance, where dialing all of the digits in quick succession without taking the time to check on steering control allowed the dialing task to be completed quickly but with significant disruption to steering. In contrast, more frequent task interleaving brought about safer driving performance (because of the decrease in time between consecutive updates of steering control) but at the cost of increasing the total time required to complete the secondary task.

A central assumption of Brumby et al.'s [4,5] modeling analysis, which will be investigated here, is that drivers are capable of adjusting dual-task strategy based on their desire to either drive better or dial more quickly. Recent studies [10,12] demonstrating that drivers are capable of prioritizing tasks give support to this idea. In one study, Horrey et al. [10] required participants to read aloud telephone numbers presented on a head-down display while driving a simulated vehicle. Experimental instructions and feedback were manipulated to encourage participants to prioritize one task or another. When drivers were instructed to give greater priority to maintaining a stable lane position, they took more time to complete the secondary task because additional glances were made to the road. These additional glances carried the benefit of improving lane keeping performance. In contrast, when participants gave greater priority to completing the secondary task, they did not invest the time in making additional glances back to the road, which necessarily brought about less stable lane keeping performance. These findings suggest that drivers can effectively adapt their strategy to experimental task demands. A weakness of Horrey et al.'s study is that the secondary task could be completed relatively quickly (the secondary task took on average only 1.16 seconds to complete), limiting the time that drivers had to actively balance attention between tasks. It seems unlikely that lane keeping performance would have declined sufficiently enough during this period of time for there to be a need for the driver to *repeatedly* interleave attention between tasks. The study reported here will further investigate how drivers adapt their strategy to varying objective while completing a secondary phone dialing task that affords multiple opportunities for attention to be interleaved between tasks.

One prominent idea for how people manage multiple tasks is that they utilize subtask boundaries as a cue to switch from one task to another [14,15,18]. The idea that task interleaving is constrained to subtask boundaries in the context of driving has been most clearly articulated in a theory put forward by Salvucci [18]. The theory assumes that task processing is controlled by a general executive, which sequentially passes subtasks through a central queuing mechanism. In this way, the completion of a subtask is seen as providing an opportunity to interleave resources between tasks with minimal disruption to performance and reduced cognitive load. Indeed, a recent study has shown that workload decreases at subtask boundaries [3].

Salvucci's [18] theory of task interleaving suggests that the structure of routine interactive skill plays a decisive role in shaping dual-task strategy, in that people should tend to shift attention between tasks on the completion of subtasks. Empirical data to support Salvucci's account come from an experiment where participants were required to enter a familiar telephone number while driving. The structural representation of the secondary dialing task followed the standard North American convention (i.e., 3-3-4 grouping of digits). In dual-task conditions, significantly elevated delays between successive keypresses were found between digits at group boundaries in the sequence (i.e., between the third and the forth digits in the sequence). Presumably, lane keeping performance improved during these prolonged delays between the completion of one subtask and the commencement of the next, but data supporting this conjecture are lacking. The study reported here will address this issue by explicitly considering how lane keeping performance changes during the completion of the dialing task. A particular question of concern is whether improvements in lane keeping are reactive to extreme drift from the lane center or whether corrections to vehicle heading are limited to the intervals between subgoals on the secondary task regardless of lane keeping performance.

In this paper we extend the analysis of a recent experiment [6] that investigated multitasking behavior in the context of driving. Participants in the study dialed a telephone number while driving a simulated vehicle. The study aimed to determine the consequences of varying the relative priority of performing each task for how these tasks were interleaved. While the original study focused only on lane keeping and total dialing time, here we examine the data at the level of individual keypress intervals and how lane keeping changed between keypresses. We also present a new computational modeling analysis that explores the nature of the behavior at the foundation of these results.

EXPERIMENT

In the original study [6], eight experienced drivers (two female) participated in a one-hour experiment. The driving task was conducted in a fixed-base driving simulator with a three-lane highway driving environment. Drivers navigated the center lane of the highway and construction cones on each side of the lane were used to discourage movement to another lane. The driver's vehicle was the only vehicle in this environment. The actual driving task required participants to steer the vehicle down the road while the simulator maintained a constant speed for the driver's vehicle (as in, e.g., [17]); the constant-speed paradigm was used so that drivers did not slow down as a response to distraction, simplifying the analysis to one of lateral deviation from lane center (though certainly this should be extended in future work).

While driving, participants occasionally dialed a 10-digit phone number on a real cellular telephone (Sony Ericsson Z710i) mounted on a hands-free bracket on the vehicle's center console. All keypresses on the phone were recorded and time-stamped through the simulation software. The dialing sequence involved pressing a "power-on" key, followed by the same 10-digit number given in the North American format (*xxx-xxx-xxxx*), followed by a "send" key to terminate the dialing task. Participants learned the phone number and practiced dialing the number on the phone in a 5-minute practice session that preceded data collection.

Single-task Conditions

In the single-task conditions, participants completed the dialing and driving tasks separately. For dialing, participants simply dialed the number as quickly and accurately as possible. At the end of each trial, they received feedback on their performance consisting of the total time to dial the number. At the end of a block of five trials, the average dialing time for the block was also shown. Participants completed two blocks of five trials.

For driving, participants were first given a practice session to allow them to become familiar with the simulator. They then drove at two speeds, either a slow speed of 35 mph or a fast speed of 55 mph, where speed was always controlled by the simulator and held at a constant value. For each speed, participants completed two blocks of five trials, with 10 seconds of driving per trial. After each trial, participants received feedback as the root-mean-squared error (RMSE) lateral deviation of the car from lane center over the 10-second trial period. Also, before the next trial would begin, participants were required to center the vehicle within +/- 0.30 m of lane center, which ensured that each trial began with the vehicle at a reasonably centered lane position. As for dialing, the average lateral deviation over a block of five trials was shown after the completion of each block.

Dual-task Conditions

In the dual-task conditions, the experiment followed a 2x2 within-subjects design with variables of task priority (focus-on-dialing; focus-on-steering) and driving speed (35-mph; 55-mph). To manipulate task priority, participants were instructed to focus on completing the dialing task as quickly as possible (the focus-on-dialing condition) or to focus on keeping the car as close as possible to lane center (the focus-on-steering condition). A trial began when the participant first pressed a key on the phone, and ended when the "send" key was pressed to terminate the dialing task. After the trial, participants received feedback *only* for the focused performance variable—that is, dialing-time feedback for the focus-on-dialing condition, and lateral-deviation feedback for the focus-on-steering condition. In total, each participant completed 80 dual-task trials: 5 trials x 4 blocks x 2 task-priority conditions x 2 driving-speed conditions.

It should be noted that, for both the dual-task and single-task conditions, the frequent presentation of feedback on performance was critical to the experiment: It encouraged participants to conform to the instruction to focus on one task or the other, and also to try to better their own 'score' through the duration of the experiment. In addition, participants were discouraged from making errors on the dialing task: If a participant made a dialing error, they had to locate and delete the incorrect key and then re-enter the correct key. In this way, making an error incurred a time cost. All error trials were excluded from the data analysis.

RESULTS

The primary dependent measures of interest were the time taken to correctly dial the phone number and the lateral deviation of the vehicle from the center of the lane. Relatively few trials were excluded from the analysis because of participant error on the dialing task. From a total of 160 single-task baseline trials for the dialing task, only 4 trials (2.5%) were excluded; from a total of 640 dual-task experimental trials, 37 (5.78%) trials were excluded. These low error rates suggest that participants were competent at using the cell phone to enter the required number correctly.

To gain an overview of the effects of interest in this study, Figure 1 shows a data plot where the elapsed time of each keypress from the start of dialing (represented on the *x*-axis) is plotted against the corresponding lateral distance of vehicle from the lane center (represented on the *y*-axis). The chunk structure of the telephone number is clearly visible in the focus-on-steering condition and there are noticeable decreases in lateral deviation in between the dialing of chunks. In contrast, when participants focused on dialing, there was no obvious delay between the entry of one chunk and the next, and the vehicle drifted steadily farther from the lane center. Driving speed clearly moderated the size of the increase in lateral deviation over time. We next describe the results of a detailed statistical analysis of the data that corroborates these initial observations. Unless otherwise stated, a 2x2 repeated measures ANOVA with the variables of task priority (focus-on-dialing; focus-on-steering) and driving speed (35-mph; 55-mph) was used for statistical analyses. An alpha-level of 0.05 was used throughout.

Dialing Task Performance

We first consider whether response times on the dialing task were slower when participants gave greater priority to steering. Responses were significantly slower when participants prioritized the steering task (*M*=7.25s, *SD*=1.71s) than when they prioritized the dialing task (*M*=4.81s, *SD*=0.87s), $F(1,7)=24.7$, $p<.001$. Moreover, the time taken to enter the number in the dual-task focus-on-dialing condition (*M*=4.81s, *SD*=0.87s) was equivalent to the time taken in the single-task dialing condition (*M*=4.67s, *SD*=0.80s). For the driving speed manipulation, there was a trend for participants to complete the dialing task more rapidly when driving at a slower speed (*M*=5.73s, *SD*=0.97s) than at a faster speed (*M*=6.33s, *SD*=1.49s), but this effect was not statistically reliable, $p=.09$. There was also no significant interaction between task priority and driving speed, $p=.32$.

While the time taken to complete the dialing task increased when participants focused on driving, this level of analysis does not show how this additional time was distributed. To support the idea that the representational structure of the telephone number influenced the strategy that was adopted, we consider the interval between consecutive keypresses within the same chunk of digits (e.g., x23-xxx, 2 vs. 3) and the interval between keypresses that were from different chunks of digits (e.g., xx3-4xx, 3 vs. 4).

Figure 2 shows that there were shorter intervals between keypresses between digits that belonged to the same chunk of numbers compared to those that were between chunk boundaries. These pauses between chunk boundaries were considerably more elevated when participants focused on steering than when they focused on dialing. In addition, when participants focused on dialing, all intervals between

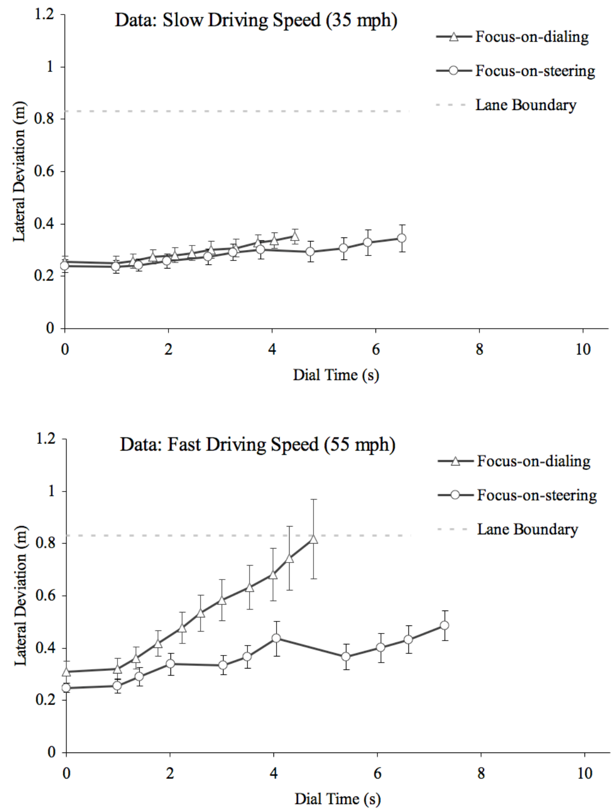

Figure 1. Data plots show changes in vehicle lateral deviation between consecutive keypress for each condition. Error bars represent standard error of mean.

keypresses were equivalent to those found in the single-task condition. For statistical analysis of this data, we used a 2x2x2 repeated measures ANOVA, which included the new variable of digit position (within-chunk; between-chunk) along with task priority and driving speed variables from before. This analysis found no effect of driving speed on the interval between keypresses, $p=.07$. There were significant main effects of digit position, $F(1,7)=8.03$, $p<.05$, and task priority, $F(1,7)=22.3$, $p<.01$. Critically, the digit position by task priority interaction was significant, $F(1,7)=13.3$, $p<.01$. Follow-up tests found that when participants focused on steering, there were significantly elevated delays between keypresses at chunk boundaries, $F(1,7)=10.45$, $p<.05$, but this effect was not reliable when participants focused on dialing, $p=.19$.

The fact that participants were giving up more time between the dialing of groups of digits is critical because it reflects a strategic difference in how they were choosing to interleave these tasks based on their objective to maintain a stable lane position while dialing. We next consider whether there were improvements in driving performance during these prolonged delays in between chunks.

Driving Task Performance

To quantify driver performance, we used a lateral deviation measure that represents the driver’s ability to maintain a

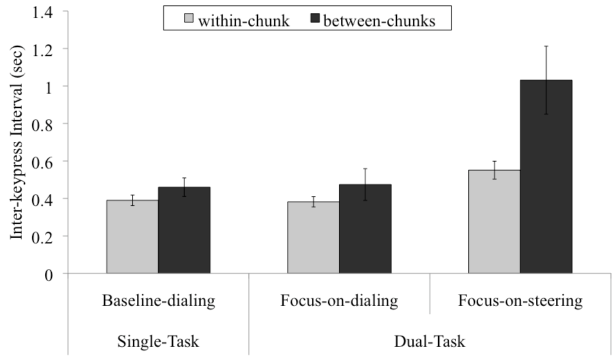

Figure 2. Effect of digit position and task priority on inter-keypress interval. Error bars are standard error of mean.

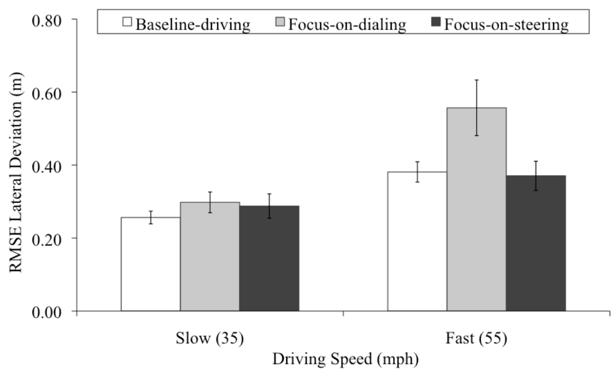

Figure 3. Effect of task priority and driving speed on RMSE lateral deviation. Errors bars are standard error of mean.

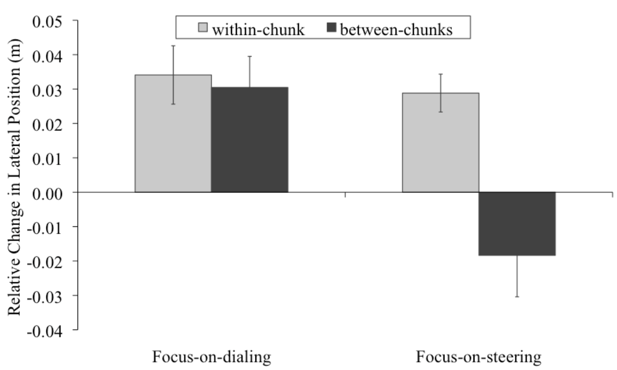

Figure 4. Effect of digit position and task priority on the relative change in vehicle lateral position in between keypresses. Error bars are standard error of mean.

central lane position over time. The driving simulator logged the lateral distance of the vehicle from the center of the lane at a rate of 200 Hz. The RMSE of these cumulative lateral deviation samples was then calculated over the period of time that the driver worked on the dialing task.

Figure 3 shows RMSE lateral deviation for single-task and dual-task conditions under varying task objectives and driving speeds. First, it is clear that driving speed affected the driver's ability to maintain a central lane position. In the single-task driving condition, a two-tailed *t*-test found that there was significantly greater lateral movement at 55-mph than at 35-mph, $t(7) = 5.40$, $p<.001$. This effect of speed on the driver's ability to maintain a central lane position was echoed across dual-task conditions, $F(1,7)=38.19$, $p<.01$.

Figure 3 also shows that lane keeping performance was affected by the driver's task objective, but only at faster driving speeds. In particular, when participants focused on the driving task, lateral deviation in the dual-task condition was more or less equivalent to that in the single-task condition. Whereas, when participants focused on the dialing task, lateral deviation was greater in the dual-task condition than in the single-task condition. Statistical analysis found a main effect of task objective on RMSE lateral deviation, $F(1,7)=5.04$, $p<.05$. There was also a significant trend for the task objective x driving speed interaction, $F(1,7)=3.64$, $p=.06$. Follow-up tests showed that at a fast driving speed, lateral deviation was greater when participants focused on the dialing task rather than the steering task, $F(1,7)=7.35$, $p=.05$. But at a slower driving speed there was not a significant simple effect of task objective on lateral deviation, $p=.76$.

To determine whether lane keeping improved during the prolonged delays between chunks in the focus-on-steering condition, we consider the relative change in lateral position between consecutive keypresses within the same chunk of digits and those between different chunks of digits. Figure 4 shows the relative change in lateral deviation between consecutive keypresses. It is clear from the figure that the *only* decrease in lateral deviation occurred between chunk boundaries in the focus-on-steering condition; lateral deviation increased between all other keypresses. A 2x2x2 repeated measures ANOVA was used for statistical analysis of data, finding main effects of task priority, $F(1,7)=25.9$, $p<.01$, and digit position, $F(1,7)=8.16$, $p<.05$. There was no effect of driving speed, $p=.09$. Critically, the task priority x digit position interaction was significant, $F(1,7)=5.75$, $p<.05$. This interaction indicates that the only improvements in lane keeping occurred between chunk boundaries in the focus-on-steering condition, $F(1,7)=10.77$, $p=.01$; there was no effect of digit position on lane keeping in the focus-on-dialing condition, $p=.75$.

DISCUSSION

The results of the study show how drivers adapt their strategy to give up more time to driving while performing a secondary dialing task. Strategy was adapted in a way that was constrained by the retrieval of hierarchical chunks associated with the dialing task. Improvements in lane keeping performance occurred only during prolonged delays between keypresses at the boundaries between chunks, and the chunk boundaries imposed such severe constraints on the adaptation of strategy that improvements in lane keeping did not appear to be reactive to changes in lane keeping. This finding suggests that drivers were systematically choosing to suspend the secondary task at the completion of a subgoal to attend to the primary task of driving.

These data support the idea that when drivers interact with a visually demanding secondary in-car device, performance is impaired because limited attentional resources have to be sequentially interleaved between tasks over time [4,5,10]. It is possible that participants could have made use of peripheral vision while dialing to monitor their lane position. We believe this possibility can be ruled out because the vehicle moved consistently farther from the lane center when participants were actively working on the dialing task and peripheral vision would have worked in favor of improved lane keeping performance while dialing.

One limitation of the current study is that eye-tracking data were not gathered. Previous studies [10] have used eye-tracking data to demonstrate how the allocation of visual attention affects driving performance. Instead of gathering eye-movement data, we infer how drivers allocated visual attention between tasks based on the duration of time between successive keypresses on the dialing task. We found that the only improvement in lane keeping came about during prolonged delays between keypresses at subgoal boundaries in the dialing task, and that the vehicle moved farther from the lane center between shorter inter-keypress intervals. This suggests that the duration of time between keypresses can be used to indicate when drivers are directing attention towards steering control. Moreover, these behavioral measures, which were relatively easy to gather and analyze, give a good indication of how drivers were choosing to allocate limited attentional resources between tasks.

The empirical data leave a number of questions unanswered. It is not clear from the data why drivers use these chunk boundaries as cues to switch from one task to the other. Is the chosen strategy rational? Would a strategy that interleaved less frequently, for instance by dialing the first six digits in sequence, achieve similar lane keeping performance? Could a strategy that interleaved more frequently achieve better lane keeping performance than one that followed the representational structure of the dialing task? To address these questions, we use a Cognitive Constraint Modeling (CCM) [11] framework to model a space of alternative task interleaving strategies and derive quantitative performance predictions for each.

MODELING STRATEGIC VARIATIONS IN BEHAVIOR

A critical component of driving involves maintaining a central lane position. Brumby et al. [4] present a high-level computational framework for understanding how secondary task interactions tend to disrupt the normal pattern of control-monitoring required for stable lane keeping performance. The model simulates a vehicle moving at a constant velocity down a straight road. The model performs a series of discrete steering updates that alter the heading (or lateral velocity) of the vehicle dependent on its position in the lane at the time that the update is performed. Like many control models (e.g., [9]), we assume that steering updates are performed to minimize perceptual input quantities that represent the lateral position and heading of the vehicle. Based on an analysis of data from two previous experiments [16,18], Brumby et al. [5] show how a simple quadratic equation can be used to formally characterize how drivers typically adjusted the heading of the vehicle given its lateral position in the roadway,

$$\textit{Velocity} = 0.2617 \times LD^2 + 0.0233 \times LD - 0.022 \quad (1)$$

The model assumes that adjustments to the lateral velocity of the vehicle are dependent on the lateral deviation, *LD*, of the vehicle at the start of the update.

The model captures the basic idea that as the vehicle strays closer to the lane boundary, drivers will tend to react by making sharper corrective steering movements, which in turn, increase the lateral velocity of the vehicle, returning it to a central lane position more rapidly. This simple model can be used to derive predictions of changes in a simulated vehicle's lateral deviation over time given discrete periods of driver attention and inattention.

The model clearly reflects idealized performance. Indeed, Brumby et al. [5] show that there is considerable variability with respect to the observed lateral velocities given at a particular starting lateral position. We account for this variability in heading adjustments by developing a simple stochastic model, in which random values are sampled from a Gaussian distribution and added to the value of the updated lateral velocity given by the simple model (Eq. 1). The Gaussian distribution had a mean of 0.00m/s and standard deviation of 0.10m/s, reflecting the average standard deviation observed in the human data.

We assume that steering updates are performed once every 250ms. This timing estimate is similar to previous steering control models [4,17,19]. In between steering updates, we assume that external factors affect the heading of the vehicle over time (i.e., bumps in the road, wind, the camber of the road). These external factors are modeled by simply perturbing the heading of the simulated vehicle every 50ms, with a random value sampled from a Gaussian distribution. The Gaussian distribution had a mean 0.00 m/s and the standard deviation was a free parameter in the model, allowing for more or less variability in heading over time. We shall see in the next section how this free parameter can be used to account for the effect of driving speed on lane keeping.

We assume that the dialing task interferes with steering control processes. Specifically, we assume that steering control updates cannot be performed while the driver has their attention directed at the dialing task. The dialing task is modeled at the granularity of the time taken to execute individual keypresses. Based on the single-task dialing data from the study, we assume that the first keypress of a new chunk (i.e., the first, fourth and seventh digit) takes 450ms, and that all other keypresses take 400ms to execute (see Fig. 2).

We assume that switching between tasks carries a cost overhead (or switch cost), which reflects the time required to move visual attention between the outside of the car (i.e., to focus on the road) and the inside of the car (i.e., to focus on the phone). Instead of developing a detailed model of the perceptual/motor processes involved, we use a simple timing estimate of 185 ms to move visual attention between the phone and the road, or vice versa. This timing estimate was taken from the ACT-R cognitive architecture [2].

Furthermore, if a strategy disrupts the chunk structure of the dialing task, then we assume that there is an additional time cost to retrieve the relevant state information from memory. Based on a more complex task model developed in the ACT-R cognitive architecture, we assume that these retrievals of state information took 100 ms to execute. This meant that the execution of keypresses could each take up to 870 ms (400 + 100 + 2 x 185) in a strategy that returned attention to driving after entering each and every digit.

Exploring the Strategy Space

We derive performance predictions for seven different plausible strategy variants for completing the dialing task while driving. The first strategy (S1) completed all keypresses in succession without once returning attention to steering control. Strategies S2-S4 used the chunk structure to signal when to switch tasks. These variants either returned attention to steering control after entering the first (S2) or second (S3) chunk of digits *only*, or after entering *both* the first and the second chunk of digits (S4). S5 invested additional time in the middle of the final chunk, steering in between the entry of the eight and ninth digit in the sequence. The remaining strategies disrupted the chunk structure by either entering digits in pairs (S6) or singly (S7), returning attention to driving after each.

For each of the different task interleaving strategies, we explored the consequences of dedicating more or less time to steering control before returning attention to dialing. As more time is given to steering control, the model is able to conduct more steering updates in succession. To understand the value of conducting multiple, successive steering updates, consider for a moment a situation where the vehicle is far from the lane center. An initial steering update will likely increase the lateral velocity of the vehicle, placing it in a sharp corrective heading in order to rapidly bring it back to the lane center (based on Eq. 1). However, left unchecked the vehicle will continue along this sharp heading, possibly passing the lane center and beyond. Further steering updates are therefore required to gradually stabilize the heading of the vehicle as it nears the lane center.

For each task interleaving strategy we systematically varied the number of steering updates that were performed, from just two steering updates performed in succession (making the total steering episode 0.5 s) to 12 steering updates being performed in succession (making the total steering episode 3 s). This upper limit was chosen because we found that conducting any more steering updates did not bring about any discernible improvement in lane keeping performance. Enumerating over this space generated 8161 strategies. Each was run for 50 trials and performance averaged.

Modeling Results

Figure 5 shows the performance predictions for each strategy variant in terms of dial time and RMSE lateral deviation at different simulated driving speeds. This strategy space essentially ranges from doing the entire dialing task without driving (all 10 keypresses in sequence) to maximally interleaving driving (with steering updates between keypresses). These extreme points in the strategy space are represented by S1 and S7. At the faster simulated driving speed (lower panel) there is a clear speed/accuracy trade-off between dialing quickly and driving safely: The upper-left portion of the plot represents faster but worse driving performance, whereas the bottom-right portion represents slower but better driving performance. In contrast, driving performance did not decline with quicker dialing at the slower simulated driving speed (upper panel).

For the model to capture the effect of driving speed, a single free parameter was varied, which determined the variability in vehicle heading over time. Recall that in between steering updates the heading of the simulated vehicle was permuted by a random value sampled from a Gaussian distribution. We identified standard deviation values for this distribution that maximized the goodness of fit between the modeled no-interleave strategy (S1) and data from the focus-on-dialing condition at each driving speed. We chose to fit data from the focus-on-dialing condition because participants tended to dial as quickly as possible without checking on steering control at all. This meant that we could directly compare the lateral deviation data at each keypress with the predicted deviation for the no-interleave strategy.

The first panel of Figure 6 shows the performance of the no-interleave strategy (S1) compared to the empirical data from the fast 55-mph focus-on-dialing condition. In the figure, the elapsed time of each keypress (represented on the *x*-axis) is plotted against corresponding lateral deviation (represented on the *y*-axis). A search of the parameter space found that a standard deviation of 0.8 m/s on the noise distribution provided a strong fit with the data (R^2 =.99). A strong fit was also found between the data from the slower driving speed and the model with a standard deviation of 0.3 m/s (R^2 =.95). (This latter model-fit is not shown because of space limitations.) With the model's no-interleave strategy fitted to data from the focus-on-dialing condition, we next use the model to account for participants' strategy in the focus-on-steering condition.

We explore the quality of fit between various task interleaving strategies and data from the focus-on-steering condition. A difficulty here is to determine the amount of time that a particular strategy should give up to steering (given that more or fewer steering updates can be performed before control is ceded back to dialing). For each strategy, we systematically explored the cost/benefit of giving up more or less time to steering control.

A simple algorithm was used to identify the point where improvements in lateral deviation asymptote with increasing time given up to steering. To do this for a given strategy, we identified all of the steering operators specified in the strategy and enumerated over a finite set of durations (500ms – 3s, at 500ms intervals). Given the strategy in this set that gave up the most amount of time to steering control, we identify a subset of strategies that do not significantly differ from it in terms of predicted RMSE lateral deviation. To this end, a series of *t*-tests were conducted to reject strategies. From this subset of strategies, which did not differ in terms of predicted lateral deviation, we select the fastest strategy (i.e., gave the least time to steering control).

The illustrative strategies S2-S7 shown in Figure 5 were selected using the algorithm described above, and represent the point for each strategy where improvements in lateral deviation asymptote with increasing time given up to steering. Inspection of the upper panel of Fig. 5 shows that at the slower simulated driving speed, the predicted RMSE lateral deviation did not differ across the various illustrative strategies, and all were within the confidence interval of the focus-on-steering data. This is to be expected at the slower driving speed, where changes in lateral deviation were slow to occur during periods of inattention.

At the faster simulated driving speed (lower panel), however, the illustrative strategies differed greatly in terms of predicted RMSE lateral deviation. But S2, S4, and S5 nonetheless gave performance predictions within the confidence intervals of the focus-on-steering data. This is interesting because each of these interleaved dialing and driving more or less often, but all appear to be equivalent in terms of lane keeping. In order to better determine how these strategies differ, we compare their performance at the level of changes in lateral deviation between keypresses.

Figure 6 shows a series of data plots where the elapsed time of each keypress is plotted against corresponding lateral deviation for S2-S6 at the faster driving speed. The focus-on-steering data is shown for comparison. By comparing strategies at this level of granularity, we see how performing fewer than two steering updates while dialing—as illustrated by S2—predicts extreme lateral deviation that brings the vehicle close to the lane boundary. This level of drift was not evident in the focus-on-steering data, where drivers were able to maintain a relatively central lane position. This is particularly interesting because the predicted RMSE lateral deviation for S2 is within the confidence interval of the human data. It is only when we compare the quality of fit between model and data at the level of changes in lane position between each keypress that we discover that this strategy fails to capture the data.

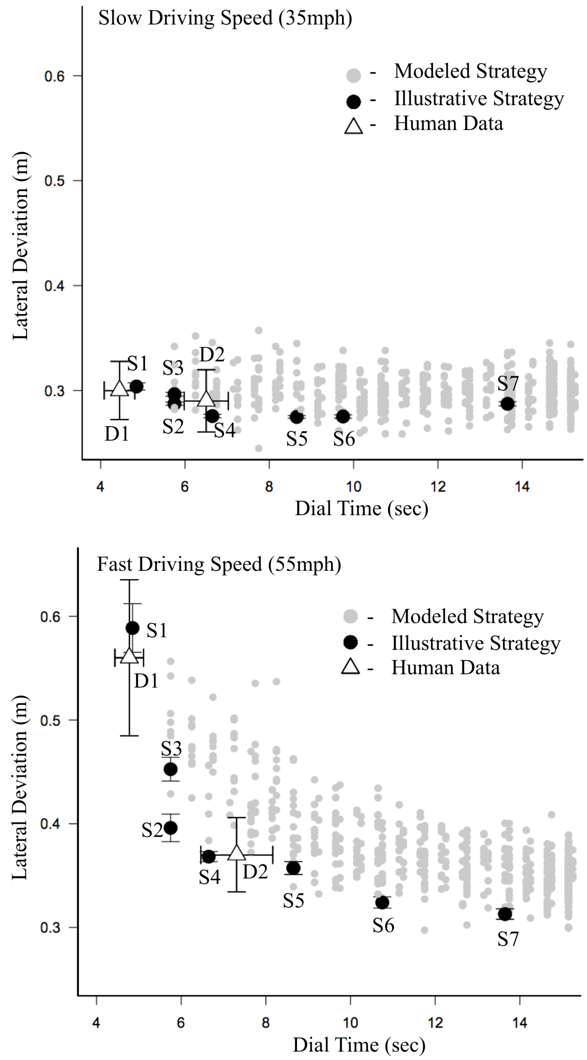

Figure 5. Predicted dial time and RMSE lateral deviation for modeled strategies and human data. Error bars represent 95% confidence intervals. D1 is focus-on-dialing data and D2 focus-on-steering data. Strategies S1-S7 shown in Fig. 6.

We also see in Figure 6 that disrupting the chunk structure of the dialing task to perform additional steering updates is inefficient and carries very little benefit to lane keeping. In particular, strategies S4 and S5 do not noticeably differ in terms of their lateral deviation profiles, but only in terms of the time required to complete the dialing task. This analysis suggests that S4—which interleaved at chunk boundaries—is particularly efficient at trading time given up to dialing with the maintenance of a central lane position.

GENERAL DISCUSSION

The results of the study suggest that the adaptations selected by participants were intricately dependent on the constraints imposed by cognition. People did adapt, but cognition imposed tight constraints on the adaptation. If it was desirable, for example, to spend more time driving than dialing, then participants did so in a manner that remained

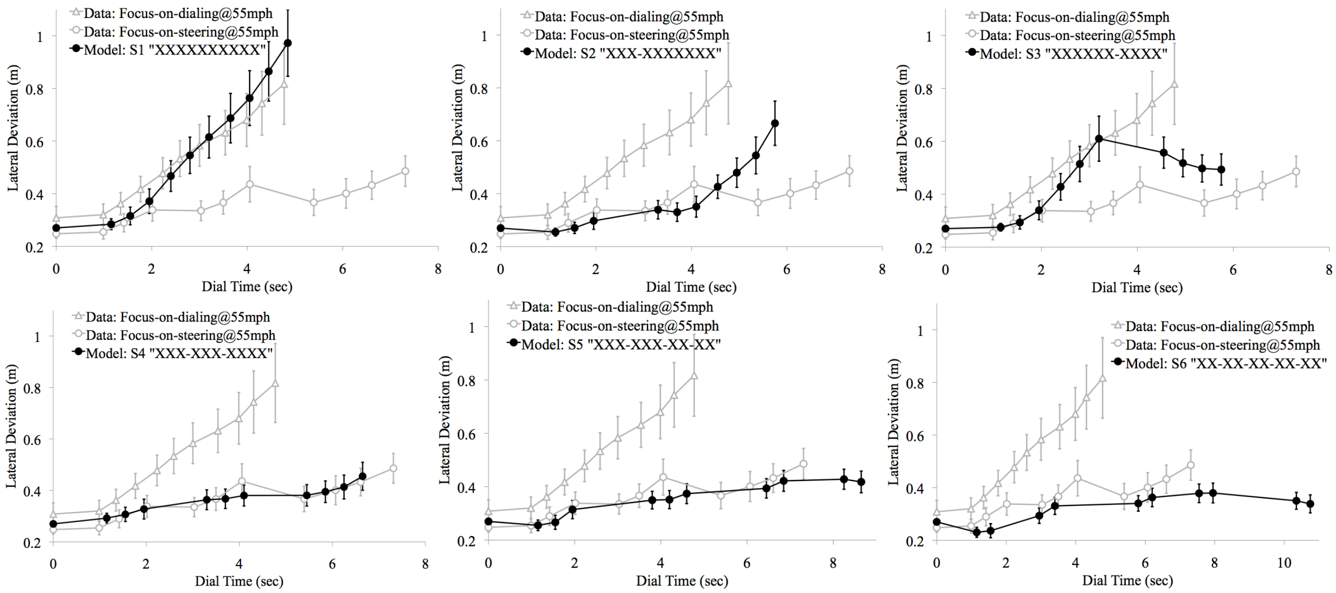

Figure 6. Data plots showing detailed performance of illustrative modeled strategies and human data. Data points represent the elapsed time of each keypress from the start of dialing and corresponding vehicle lateral deviation.

sensitive to the internal psychological constraints on the retrieval of hierarchical chunks associated with the dialing task. The consequences of cognitive constraints is evident in the fact that improvements in driving performance (i.e., where the car is brought closer to the lane center) only occurred during prolonged periods between chunk boundaries. Lateral deviation generally increased during periods where the driver was actively engaged in working on the secondary dialing task, and decreased during discrete periods in which dialing was suspended.

Moreover, the chunk boundaries appeared to impose such severe constraints on adaptation that improvements in lane keeping did not appear to be reactive. It is clear that drivers took the opportunity to invest the time on improving lane keeping in between chunks, regardless of how far the vehicle had drifted from the center of the lane. For instance, after dialing the first chunk of digits, the vehicle was still fairly close to the lane center, but drivers nonetheless invested time before commencing with the next burst of keypresses. It is not immediately clear why drivers would choose to give up time to steering here since there is limited scope for improvement in lane keeping.

A computational modeling analysis was conducted to better understand why drivers might have favored a strategy that interleaved attentional resources at chunk boundaries over alternative strategies. The model was used to systematically explore a space of plausible interleaving strategies and derive quantitative performance predictions for each. The analysis showed that not returning attention to steering control at least twice while dialing resulted in extreme lane deviation. In particular, the analysis shows how an early correction to steering control immediately after the dialing of the first chunk of digits acts to counter an extreme deviation occurring during the dialing of the second chunk of digits. This helps explain one of the nuisances of the empirical data, where it appears as though participants are investing time in steering control even though the vehicle is already close to the lane center: the benefit of this correction to steering control is to be had down-stream. In contrast, disrupting the chunk structure in order to perform additional steering updates is inefficient because doing so incurs considerable time costs but brings about only modest improvements in lane keeping. These insights could not have been gleaned from the empirical data, which only show how people actually behaved. Cognitive modeling was useful in this context for rigorously exploring a space of plausible human behaviors in order to better understand why people behave the way they do.

The computational modeling approach taken here focused on understanding the constraints on the interaction between the driver and the task environment important to critical performance variables (e.g., lateral deviation and dial-time). This could contribute to work aimed at developing tools for modeling driving behavior, such as Distract-R [20], which can be used to identify interaction designs for safer in-car systems. The work presented contributes to this enterprise by offering a parsimonious account of steering control processes, in which a simple quadratic function is used to capture the idea that drivers tend to steer towards the lane center when the vehicle is far from the lane center but tend to keep a straight heading when the vehicle is close to the lane center. These model-based predictions have been derived from an analysis of existing steering control data [17,19]. Additional work is required to corroborate the model and identify a plausible range of parameters that are reliable across a broad range of participants and driving environments.

One concern with the generalizability of the findings of this paper is that the driving task was artificially simple. In the study participants were required to drive a vehicle down a straight highway with no other vehicles in the roadway and without controlling speed. Because we found strong effects in this simple driving task between the various dual-task conditions, this probably provides a conservative measure of the effect of objective on performance in real-world settings, where driving is typically more demanding. Indeed, previous studies [16] have shown that effects found in driving simulators are typically also found in the real world (though sometimes the size of the effect may be different).

In contrast, the finding that drivers in the dual-task focus-on-steering condition were able to drive just as well as those in the baseline, single-task condition is more than likely an artifact of the simple driving task environment. It seems unlikely that drivers would be able to adapt their multitasking strategy sufficiently to drive "safely" in a more demanding driving environment. Perhaps a slightly more interesting question to ask is whether drivers are sensitive to the changing demands of a typical real-world driving environment, and if they are, whether they adapt by perform secondary in-car tasks only during less demanding periods of driving. It would also be interesting to see how drivers adapt when a step in a secondary in-car task takes substantially longer to complete than they are willing to take their eyes away from the road for. An answer to this latter question would give some indication of whether people are willing to incur the costs of disrupting the structure of secondary task processing—if not, then lengthy, demanding interactions might present a particular safety hazard in the context of an on-going safety critical control-monitoring task like driving.

CONCLUSION

Given that people continue to engage in secondary tasks while driving, there may be substantial value in developing a greater understanding of how people adapt their strategy so as to inform the design of systems to reduce demand on the driver. The results of this study show that changing drivers' objectives can affect how they choose to adapt. The total time that the driver is distracted is less important than the extent to which they are encouraged to make quick glances back to the road while actively working on the secondary task. However, strategy adaptation can be severely constrained by the representational structure of the secondary task. This suggests that designing mobile devices that facilitate short bursts of interaction as opposed to requiring long stretches of interaction might help to alleviate some of the deleterious effects of distraction.

ACKNOWLEDGMENTS

This research was supported by NSF grant #IIS-0426674. We thank Richard Young and five anonymous reviewers for their detailed comments on an earlier draft of this paper.

REFERENCES

1. Alm, H. & Nilsson, L. (1995). The effects of a mobile telephone task on driver behavior in a car following situation. *Accident Analysis and Prevention, 27*, 707–715.
2. Anderson, J.R., Bothell, D., Byrne, M.D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of mind. *Psychological Review, 111*, 1036-1060.
3. Bailey, B.P., & Iqbal, S.T. (2008). Understanding changes in mental workload during execution of goal-directed tasks and its application for interruption management. *ACM Transactions on Computer-Human Interaction, 14*, 1-28.
4. Brumby, D.P., Howes, A., & Salvucci, D.D. (2007). A cognitive constraint model of dual-task trade-offs in a highly dynamic driving task. *Proc. SIGCHI Conf. on Human Factors in Computing Systems* (233-242). ACM Press.
5. Brumby, D.P., Salvucci, D.D., & Howes, A. (2007). Dialing while driving? A bounded rational analysis of concurrent multi-task behavior. *Proc. 8th International Conf. on Cognitive Modeling* (121-126). Taylor & Francis.
6. Brumby, D.P., Salvucci, D.D., & Howes, A. (2007). An empirical investigation into dual-task trade-offs while driving and dialing. In *Volume 2 Proc. of the 21st BCS HCI Group Conf.*. BCS.
7. Card, S.K., Moran, T.P., & Newell, A. (1983). *The Psychology of Human-Computer Interaction*. Hillsdale, NJ: LEA.
8. Eng, K., Lewis, R.L., Tollinger, I., Chu, A., Howes, A., & Vera, A. (2006). Generating automated predictions of behavior strategically adapted to specific performance objectives. *Proc. SIGCHI Conf. on Human Factors in Computing Systems* (621-630). ACM Press.
9. Hildreth, E., Beusmans, J., Boer, E., & Royden, C. (2000). From vision to action: experiments and models of steering control during driving. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 1106–1132.
10. Horrey, W.J., Wickens, C.D., & Consalus, K.P. (2006). Modeling drivers' visual attention allocation while interacting with in-vehicle technologies. *Journal of Experimental Psychology: Applied, 12*, 67-78.
11. Howes, A., Vera, A., Lewis, R.L., (2007). Bounding rational analysis: Constraints on asymptotic performance. In W.D. Gray (Ed.) *Integrated Models of Cognitive Systems* (403–413). Oxford University Press.
12. Levy, J., & Pashler, H. (2008). Task prioritization in multitasking during driving: Opportunity to abort a concurrent task does not insulate braking responses from dual-task slowing. *Applied Cognitive Psychology, 22*, 507-525.
13. Meyer, D.E., & Kieras, D.E. (1997). A computational theory of executive control processes and human multiple-task performance: Part 1. Basic mechanisms. *Psychological Review*, 104, 3-65.
14. Miyata, Y., & Norman, D.A. (1986). Psychological issues in support of multiple activities. In D.A. Norman & S.W. Draper (Eds.), *User Centered System Design: New Perspectives on Human-Computer Interaction* (265-284). LEA.
15. Payne, S.J., Duggan, G.B., & Neth, H. (2007). Discretionary task interleaving: Heuristics for time allocation in cognitive foraging. *Journal of Experimental Psychology: General, 136*, 370-388.
16. Reed, M.P., & Green, P.A. (1999). Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialing task. *Ergonomics, 42,*1015-1037.
17. 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.
18. Salvucci, D.D. (2005). A multitasking general executive for compound continuous tasks. *Cognitive Science, 29*, 457-492.
19. Salvucci, D.D., & Macuga, K.L. (2002). Predicting the effects of cellular-phone dialing on driver performance. *Cognitive Systems Research, 3*, 95-102.
20. Salvucci, D.D., Zuber, M., Beregovaia, E., & Markley, D. (2005). Distract-R: Rapid prototyping and evaluation of in-vehicle interfaces. *Proc. SIGCHI Conf. on Human Factors in Computing Systems* (581-589). ACM Press.
21. U.S. Department of Transportation. *National Transportation Statistics 2006*. U.S. Government Printing Office.