Predicting the effects of cellular-phone dialing on driver performance

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Abstract

Legislators, journalists, and researchers alike have recently directed a great deal of attention to the effects of cellular telephone ('cell phone') use on driver behavior and performance. This paper demonstrates how cognitive modeling can aid in understanding these effects by predicting the impact of cell-phone dialing in a naturalistic driving task. We developed models of four methods of cell-phone dialing and integrated these models with an existing driver model of steering and speed control. By running this integrated model, we generated a priori predictions for how each dialing method affects the accuracy of steering and speed control with respect to an accelerating and braking lead vehicle. The model predicted that the largest effects on driver performance arose for dialing methods with high visual demand rather than methods with long dialing times. We validated several of the model's predictions with an empirical study in a fixed-based driving simulator. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

Driving is a highly complex skill that requires the continual integration of interdependent perceptual, motor, and cognitive processes. Nevertheless, driving becomes routine enough for many of us that we can comfortably perform minor secondary tasks while driving — for instance, turning on headlights or adjusting the defogger. However, technological advances now enable the incorporation of increasingly sophisticated devices in the vehicle for both driver

support (e.g. navigation aids) and 'infotainment' (e.g. news and email). In particular, cellular telephones (or 'cell phones') have received a great deal of attention related to the potentially distracting effects of cell-phone use while driving (e.g. Alm & Nilsson, 1995; McKnight & McKnight, 1993; Reed & Green, 1999; Serafin, Wen, Paelke, & Green, 1993). While it may be convenient to have devices such as cell phones available for driver use, safety is clearly the primary concern, and thus it is essential that we understand the impact that in-car devices may have on driver behavior and performance.

This paper demonstrates how cognitive modeling can aid in this effort by predicting the effects of

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secondary devices on driver performance. In particular, we focus on the task of cell-phone dialing and the impact that dialing has on driving. To this end, we utilize an integrated modeling approach that centers on combining cognitive models of the primary and secondary tasks into a single integrated model (Salvucci, 2001; see also Aasman, 1995). We begin with a task analysis of cell-phone dialing for four distinct dialing methods and describe straightforward models for these methods implemented in the ACT-R cognitive architecture (Anderson & Lebiere, 1998). We then combine the dialing models with an existing ACT-R model of driver behavior (Salvucci, Boer, & Liu, in press), producing an integrated model that can interleave dialing and driving. Finally, we run the integrated model to generate behavioral protocols, which in turn embody a priori predictions about the effects of the dialing on driving (and vice-versa).

This study improves and extends an initial modeling study of cell-phone dialing and driving (Salvucci, 2001) in two important ways. First, the previous study used a simplified cell-phone interface with a non-functional phone keypad and examined four invented dialing methods based on this interface. In contrast, this study uses a commercially available cell phone and examines four dialing methods built into this phone. Second, the previous study involved a simpler task in which drivers dialed the phone while steering down a single-lane straight road at a constant speed. In contrast, this study involves a more complex and naturalistic environment in which drivers dial while navigating down a curvy lane in a construction zone and following lead cars at highly varying speeds. These two aspects of the new study provide increased realism and allow us to predict and examine the effects of dialing not only on driver steering but also on driver speed control during car following in a naturalistic task. We should note that while conversation on cell phones may also impact driver behavior, this study focuses specifically on the dialing component of cell-phone use.

2. The driving and dialing task

In studying the effects of cell-phone dialing on driving, we desired a task in which both the dialing and the driving would be as realistic and natural as possible. However, for the driving task, potential safety concerns as well as legal restrictions due to driver distraction precluded the use of an actual vehicle on real roadways. Thus, we chose a task in which drivers navigated a naturalistic roadway in our medium fidelity driving simulator (Beusmans & Rensink, 1995). The simulated environment was a three-lane highway in a construction zone with driving restricted to the center lane, as shown in Fig. 1. The road alternated between segments of straight roadway and segments of various curvatures, all of which could be negotiated comfortably at highway speeds without braking. The driver followed three cars and was tailed by another car, which was visible in the simulated rear-view mirror. The speed of the lead car varied from 5 to 35 m/s (11–78 mph) according to a sum of three sinusoids that resulted in an apparently random pattern. The rear car followed at distance of 9–21 m (29–68 ft) also varying as the sum of three sinusoids. Cones on either side of the center lane prevented drivers from passing other cars and emphasized the need for maintaining a central lane position. Thus, the cell-phone dialing scenario could be thought of in terms of the driver being caught up in a construction zone and needing to call several people to notify them of a delay.

For the dialing task, we employed a commercially available cell phone (Samsung SCH-3500® with Sprint PCS®), shown in Fig. 2. This phone (like many similar phones) allows for multiple methods of dialing. In order to examine differential effects of various dialing methods, we chose four of the phone's built-in methods, which can be described as follows:

- *Manual*: dial the phone number and press **Talk**
- *Speed*: dial the party's single-digit 'speed number' and press **Talk**
- *Menu*: press the up arrow to access menu, scroll down to the desired party with the down arrow, and press **Talk**
- *Voice*: press and hold **Talk**, say the party's name when prompted, and wait for confirmation

Table 1 shows examples of using each of these dialing methods to make a call. Note that two of the methods, speed and menu dialing, require that numbers be added to an internal phone book and associated with a unique 'speed number'. The four
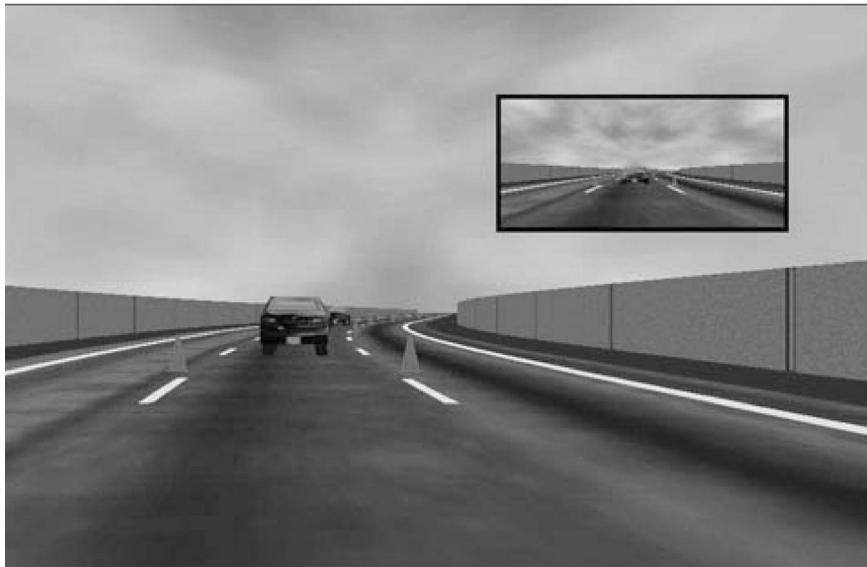
Fig. 1. Driving task environment, shown as a sample scene from the driving simulator with construction cones, lead cars, and rear-view mirror.

Fig. 2. Cell phone and keypad.

methods thus serve well to illustrate our modeling approach for comparing effects of different dialing methods on driver performance.

3. The integrated dialing-driving model

The prediction of effects of dialing on driving centers on an integrated cognitive model that combines individual models for each task. To facilitate the development and integration of these models, we implemented the models in the ACT-R cognitive architecture (Anderson & Lebiere, 1998). ACT-R is a production system architecture based on condition–action rules that execute the specified actions when the specified conditions are met. Like most cognitive architectures, ACT-R provides a rigorous framework for cognitive models as well as a set of built-in parameters and constraints on cognition and perceptual–motor behavior (when using ACT-R/PM: Byrne & Anderson, 1998); the parameters facilitate a priori predictions about behavior, while the constraints facilitate more psychologically (and neurally) plausible models. In addition, the architecture allows for straightforward integration of models of multiple tasks: generally speaking, the modeler can combine the models' rule sets and modify the rules to interleave the multiple tasks (see Salvucci, 2001). All these qualities of the architecture are essential to our ability to integrate models of dialing and driving to predict the effects of each task on the other.

3.1. Dialing models

We first consider the development of the cognitive models for dialing the cell phone using each of the four methods. To this end we employed a straight-

Table 1
Cell-phone dialing methods with examples and task models

Method	Manual	Speed	Menu	Voice
Sample call	Press 8, 6, 7, 5, 3, 0, 9 Press **Talk**	Press 3 Press **Talk**	Press ▲ (display menu with first item selected) Press ▼, ▼ (scroll down to third item) Press **Talk**	Press and hold **Talk** Hear prompt Say 'Jenny' Hear 'Jenny' Hear 'Connecting . . .'
Model outline	Recall phone number Move hand to phone ⇑ Attend to phone Recall number block Press digit (repeat until last digit) Press last digit ⇑ (repeat until last block) Attend to phone Press **Talk** ⇑ Move hand to wheel ⇑	Recall speed number Move hand to phone ⇑ Attend to phone Press speed number ⇑ Attend to phone Press **Talk** ⇑ Move hand to wheel ⇑	Recall speed number Move hand to phone ⇑ Attend to phone Press ▲ ⇑ Attend to phone Press ▼ (repeat until speed number is reached) ⇑ Attend to phone Press **Talk** ⇑ Move hand to wheel ⇑	Move hand to phone ⇑ Attend to phone Press **Talk** ⇑ Move hand to wheel ⇑ Confirm prompt Say name ⇑ Confirm name ⇑ Confirm connection ⇑

Sample calls are based on calling 'Jenny' at the number 867-5309 with speed number 3. The model outlines include sequences of steps in which each step is implemented in the model as an ACT-R production rule. Steps marked with ⇑ indicate that the model cedes control to the driving task after executing the step.

forward task analysis and implemented a simple, minimal model for each method based on this analysis. The procedure required by the cell phone highly constrains the model in that it specifies the sequence of keypresses needed to dial. However, the model must also incorporate the cognitive and perceptual processes needed to execute the procedure.

Table 1 includes an outline of the dialing models for each method. We employed a few simple rules to augment the basic procedures with cognitive and perceptual processes. First, we assumed that drivers look at the phone to guide their keypresses and that they group these keypresses in small blocks to minimize the time during which the eyes are off the road. Second, we assumed that for the manual condition, drivers chunk their keying of the seven-digit number as a sequence of three, two, and two digits, for the purposes of keeping working memory load low in addition to minimizing off-road gaze time. Third, we assume that drivers move their right hand to the phone just before the first keypress and move back to the steering wheel just after the final keypress. Of course, these assumptions may not hold for all drivers; for instance, drivers very familiar with dialing on this particular phone may be able to

type by feel without looking. However, these models nicely represent drivers who are familiar with using cell phones but are beginners or intermediates at using the phone while driving.

3.2. Driving model

To model driver behavior, we employed an existing ACT-R model that drives in naturalistic simulated highway environments, including multi-lane highways with other vehicle traffic (Salvucci et al., in press). In essence, this model controls steering and speed based on two salient visual features of the roadway: the 'near point' centered immediately in front of the vehicle, which guides lane positioning; and the 'far point' — either a distant roadway point or a lead vehicle — which guides prediction and response to the upcoming road. These features are encoded and control is updated through an augmented version of ACT-R's perceptual–motor mechanisms (ACT-R/PM: Byrne & Anderson, 1998). The model in the initial study (Salvucci, 2001) included and tested only the steering component of the model; this study includes and tests both the steering and speed control components of the model, allowing us

to examine for similar and/or parallel effects across modalities.

Although space constraints here preclude a full description of the driver model, we should note two important aspects of the model that are critical to this study. First, because of its implementation in the ACT-R architecture, the model has very limited parallelism (in its perceptual–motor modules) and thus must encode the visual scene and update control in a sequential fashion. When the model performs secondary tasks, its processing for these tasks takes away from processing of the primary driving task, and thus the model cannot update control as frequently. Second, the model generates time-stamped behavioral protocols through its perceptual–motor modules, including both vehicle control and eye-movement data. This aspect facilitates straightforward comparison between model and human behavior for effects of cell-phone dialing on driving using the same standard metrics, as discussed in the next section.

3.3. Integrated model

As mentioned earlier, the integration of the dialing and driver models is accomplished by combining the rule sets and modifying them slightly such that the integrated model interleaves both tasks. The integrated model in this study was formed in this straightforward manner, just as the integrated model in the initial study (Salvucci, 2001). Briefly, the driver model decides on each control cycle whether it can safely perform a secondary task for a short time; this decision depends on several aspects of the environment, such as stability of the near and far points, lane position, and time headway. If the model determines that the car is stable, it passes control to the dialing model. After some incremental processing (described below), the dialing model passes control back to driving and the driver model again handles the primary task.

The primary difficulty of integration arises in determining when the dialing model should cede control back to the driver model. As in the initial study, we determined these points through task analysis and a simple heuristic: any step that would block and wait for some process to complete — for instance, moving the hand to the phone or listening

for a prompt — should cede control to the driver model. The exception to this rule arises in the perceptual processes: because the dialing models are required to look at the phone during keypresses (by assumption), they must wait for the eyes to reach the phone and then execute a short block of keypresses before ceding control. The determination of these blocks was performed by task analysis; for instance, for menu dialing, we assumed that drivers press the down arrow quickly in succession to scroll down to the desired party, and that they maintain their gaze on the phone for both keypresses and monitoring the phone display. The steps after which the dialing models cede control to driving are indicated in Table 1 with the symbol ⇑.

One final concern for the integrated model is the setting of parameter values. Almost all parameter values in the integrated model were ported directly from the integrated model in the initial study (Salvucci, 2001). We changed the value of one parameter, the desired following time headway, from 1 to 2 s to better represent how drivers fall back from a lead car when they expect a high workload (i.e. dialing the phone). We also assumed a 1-s duration for the speech signal representing the dialed party's name for the voice dialing method.

4. Model simulation and validation

Given the integrated model, we generated behavioral protocols and examined the model's a priori predictions about the effects of dialing on driving. In addition, we collected analogous protocols from human drivers performing the dialing–driving task in a fixed-base driving simulator. This section describes the collection of these data and the comparison and validation of the model's predictions to the human data.

4.1. Model simulations

The model was given the simulator driving task (see Fig. 1) starting behind the lead car at a full stop. After 1 min of driving to accelerate to highway speed, the model was made to dial the cell phone using one of the four methods. When dialing was completed, the model drove normally for 20 s until

again made to dial the phone. This continued at 20-s intervals until the model had dialed 8 times using each of the four dialing methods for a total of 32 trials in a driving session. We ran a total of 8 model sessions. Separately, we ran another 8 sessions in which the model simply dialed the phone without driving, thus giving us baseline data on the model's dialing times.

4.2. Empirical study

Seven licensed subjects between the ages of 18–40 with at least 2 years of driving experience participated in the experiment. Subjects each performed one session of the driving task in the Nissan Cambridge Basic Research driving simulator (Beusmans & Rensink, 1995). The phone (with headset) was mounted on the center console positioned just to the right of the steering wheel, so that the subject could dial without holding the phone. Before driving, subjects listed four regularly-dialed phone numbers and practiced dialing these numbers with each of the four methods. Subjects then completed a driving session completely analogous to that for the model: after an initial one minute, the experimenter asked the subject to dial the phone using a particular method (in a blocked manner, such that all calls using one method occurred consecutively). The data thus comprised 32 dialing trials (8 trials per method) per subject. Collected data included vehicle control data as well as eye-movement data using an IScan (Burlington, MA) head-mounted eye tracker. In addition, prior to and following the driving session, baseline dialing time data were collected with subjects dialing without driving.

4.3. Results

Fig. 3 shows the results for both the model simulation and the human drivers. The results include analysis along four measures: dialing time, or time to complete dialing either with driving or without driving ('baseline'); lateral deviation, or RMS error of the vehicle's lane position with respect to the lane center; speed deviation, or RMS error of the vehicle's speed with respect to the speed of the lead vehicle; and gazes to the phone.

The model's predictions for dialing time indicate that voice and manual dialing require the most time while speed and menu dialing require the least. Dialing times increase approximately half a second to 3 s while driving. These predictions, which arise primarily from ACT-R's perceptual–motor parameters and the specification of the models from task analysis, correspond very well to the human data, $R > 0.99$.

The predictions for lateral deviation and speed deviation indicate the effects of dialing on driver performance. The model predicts increasing deviations for the methods in the order of voice, speed, menu, and manual dialing. For both measures, manual dialing results in deviations much greater than any of the other methods. Compared to the human data, we see a similar overall pattern with lower deviations for voice and speed dialing and higher deviations for manual dialing. However, human drivers exhibited similar deviations for menu and manual dialing. We suspect that the cognitive time required for human drivers to retrieve the speed number as needed for menu and speed dialing was larger than the model predicted, and thus the model underpredicted the performance effects in these conditions. In addition, the magnitudes of the model predictions are approximately half those for the human drivers (note the different graph scales); however, it should be noted that effects in driving simulators are commonly larger than those in real-world field studies (Reed & Green, 1999). In any case, the model seems to capture the basic rank-order effects of the various dialing methods, $R = 0.65$ for lateral deviation, $R = 0.75$ for speed deviation.

The model also predicts the mean total time of gazes to the phone per dialing trial. While these predictions are related to our task analysis in determining the frequency of phone gazes, they do incorporate emergent predictions of gaze durations and illustrate how the dialing methods differ with respect to visual demands. The model and human data correspond well, $R > 0.99$.

Taken together, the model predictions suggest that total dialing time does not seem to be a good indicator of the effects of a given dialing method on driver performance (as measured by lateral and speed deviations): although voice dialing required the most time, it produced the smallest deviations, while two faster methods, speed and menu dialing, produced
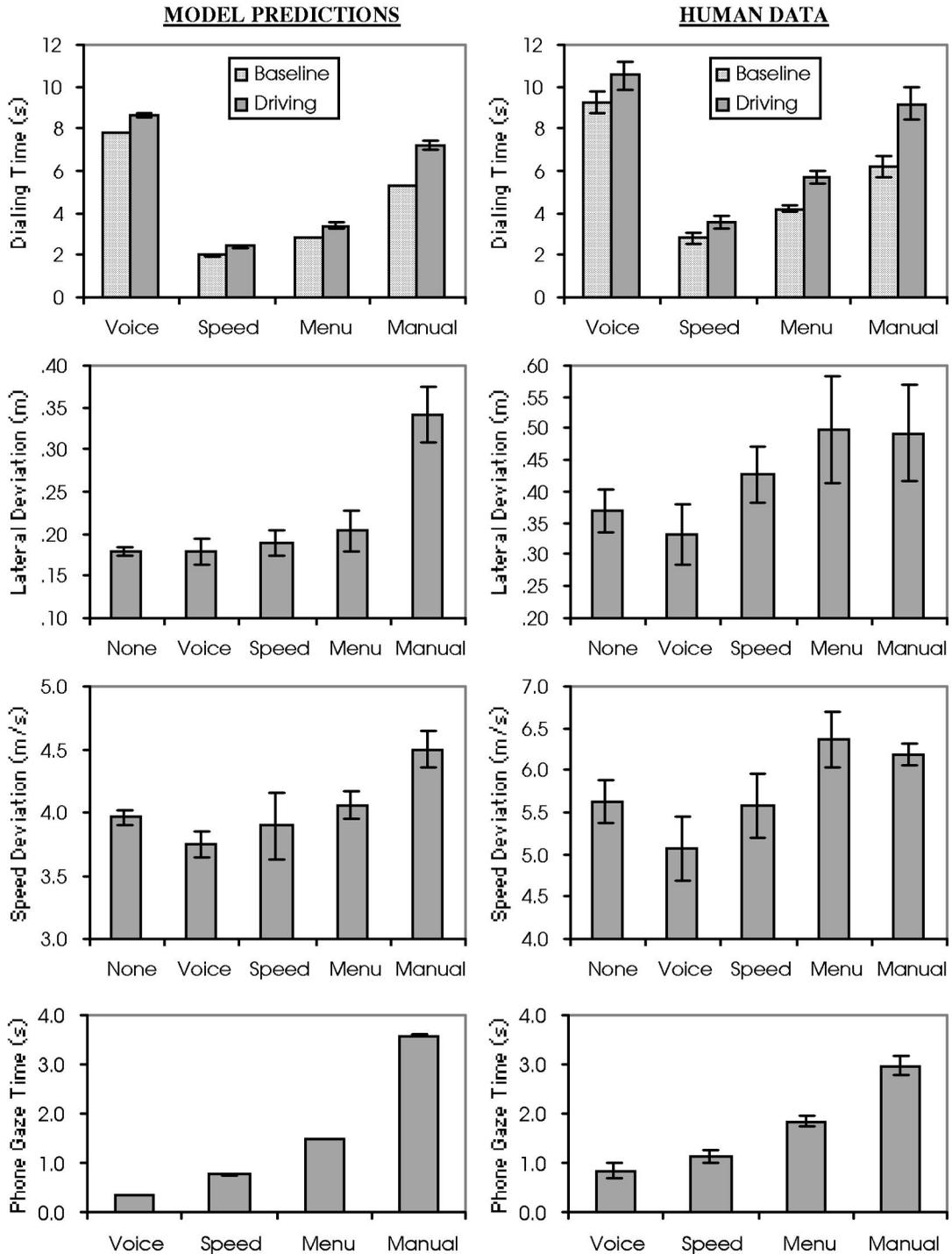
Fig. 3. Results for the model simulations (left) and human drivers (right) for the four analyzed measures: dialing time, lateral (lane) deviation, speed deviation, and gaze time at phone per dialing trial. Error bars for the human data represent standard errors of subject means; bars for the model predictions represent standard errors over simulation run means. Note that some adjacent graphs are plotted on different scales to best display the overall patterns.

larger deviations. Instead, visual demand as measured by phone gazes does seem to be a good indicator of the effects of a method on driver performance: the methods with the least visual demand resulted in the smallest deviations and vice-versa. These predictions are confirmed by the empirical data. Of course, this does not mean that visual demand is the only contributor to driver distraction — for instance, conversation and conversation-like tasks seem also to affect driver behavior (see Serafin et al., 1993, for a review).

5. Conclusions

We have demonstrated that the integrated model approach helps to predict and evaluate the effects of cell-phone dialing on driver performance. However, the approach can be generalized to assess arbitrary on-board interfaces such as navigation devices, climate controls, and 'infotainment' systems. Given an arbitrary interface, a straightforward task analysis can be performed to develop new models of behavior for the interface, as is common with modeling frameworks such as GOMS (Card, Moran, & Newell, 1983). By integrating these models with the driver model, developers can predict and compare the effects of different interfaces and narrow down the number of interfaces to analyze more rigorously through prototyping and field testing. We hope that the integrated model approach can thus facilitate the development and testing of safer, less distracting on-board systems and devices.

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