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Predicting the effects of in-car interface use on driver performance: an integrated model approach

DARIO D. SALVUCCI

Department of Math and Computer Science, Drexel University, 3141 Chestnut St., Philadelphia, PA 19104, USA. email: salvucci@mcs.drexel.edu

AND

Nissan Technical Center, North America. email: dario@cbr.com

While researchers have made great strides in evaluating and comparing user interfaces using computational models and frameworks, their work has focused almost exclusively on interfaces that serve as the only or primary task for the user. This paper presents an approach of evaluating and comparing interfaces that users interact with as secondary tasks while executing a more critical primary task. The approach centers on the integration of two computational behavioral models, one for the primary task and another for the secondary task. The resulting integrated model can then execute both tasks together and generate *a priori* predictions about the effects of one task on the other. The paper focuses in particular on the domain of driving and the comparison of four dialing interfaces for in-car cellular phones. Using the ACT-R cognitive architecture (Anderson & Lebiere, 1998) as a computational framework, behavioral models for each possible dialing interface were integrated with an existing model of driver behavior (Salvucci, Boer & Liu, in press). The integrated model predicted that two different manual-dialing interfaces would have significant effects on driver steering performance while two different voice-dialing interfaces would have no significant effect on performance. An empirical study conducted with human drivers in a driving simulator showed that while model and human performance differed with respect to overall magnitudes, the model correctly predicted the overall pattern of effects for human drivers. These results suggest that the integration of computational behavioral models provides a useful, practical method for predicting the effects of secondary-task interface use on primary-task performance.

1. Introduction

As ubiquitous computing becomes more prevalent in our daily lives, user interfaces are increasingly moving off the desktop and into the external world. This "mobilization" of user interfaces is leading to a rethinking of how we design and evaluate interfaces for future ubiquitous systems. One of the most critical issues for today's ubiquitous interfaces is the demand for users' limited attention as they navigate the external world. Whereas interfaces on the desktop are typically the primary focus of a person's attention, interfaces away from the desktop are typically one of potentially many other tasks that a person must manage and perform. This issue becomes most crucial for domains in

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which the use of the interface is secondary or peripheral to some performance-critical primary task. For instance, in the domain of driving, safe navigation through continual steering and speed control clearly serves as drivers' primary task; however, drivers engage in a wide variety of secondary tasks through interaction with in-car interfaces for devices such as radios, climate controllers, and cellular phones. The design and evaluation of such interfaces, which we call *secondary-task interfaces*, must clearly take into account not only how easily a person can interact with the interface but also the (possibly adverse) effects of interface use on behavior and performance in the primary task.

This paper demonstrates a novel approach of evaluating and comparing secondary-task interfaces using a cognitive architecture. A cognitive architecture (or simply "architecture" in this exposition) is a framework for building computational process models of thought and behavior (e.g. Soar: Laird, Newell & Rosenbloom, 1987; Newell, 1990; EPIC: Kieras & Meyer, 1997; ACT-R: Anderson & Lebiere, 1998). The framework constrains the specification of such models and also incorporates the parameters of the execution of this behavior, such as the time needed to recall a memorized fact or to type a letter on a keyboard. Architectural models can thus make *a priori* predictions concerning behavior in a given task, allowing practitioners to evaluate an interface's usability and compare the interface to other interfaces for the task. The GOMS framework (Card, Moran & Newell, 1983) and extensions of this framework (e.g. NGOMSL: Kieras, 1988; CPM-GOMS: John, 1990) are perhaps the most widely used architectures for this purpose and have been successfully utilized to evaluate and compare interfaces in numerous real-world domains (e.g. Gray, John & Atwood, 1993; see John & Kieras, 1996, for a review). However, the application of GOMS and other frameworks has to date focused almost exclusively on primary-task interfaces (i.e. interfaces assumed to be the primary focus of the user's attention) rather than secondary-task interfaces in the presence of a performance-critical primary task. This paper demonstrates how cognitive architectures can also facilitate the design and development of secondary-task interfaces.

The approach centers on the development and integration of individual models for the primary and secondary tasks. First, models are constructed to represent behavior in each task by itself—that is, behavior when a person need perform only that one task. Second, the primary- and secondary-task models are combined to form an integrated model that can perform both tasks together (perhaps interleaved, perhaps simultaneously to a limited extent, as dictated by the architecture). The integration makes use of a central characteristic of (typical) cognitive architectures that allow for modular development of behavioral models in subtasks of a larger task to form high-level models for complex domains. The integrated model, when instructed to perform both tasks together, generates both qualitative and quantitative predictions about the resulting integrated behavior and thus the effects of one task on the other. These predictions can be used in turn to evaluate how easily users can interact with the secondary-task interface and what effects the interface has on primary-task performance.

This paper focuses on the domain of driving and the effects of dialing a cellular telephone (or "cell phone") on driver performance. With cell-phone use increasing at a rapid rate, legislators, researchers, politicians and the media have all taken close looks at the effects of cell-phone use on driver performance and roadway safety. Much of this attention emphasizes conversations over the phone and the effects of holding a phone and conversing while driving (e.g. Brookhuis, de Vries & de Waard, 1991; McKnight & McKnight, 1993; Alm & Nilsson, 1994; Redelmeier & Tibshirani, 1997). With a few exceptions (e.g. Serafin, Wen, Paelke & Green, 1993*a*, *b*), less attention has been paid to the process of dialing the phone and the effects of cell-phone dialing using different types of interfaces. This paper expands on an initial study (Salvucci, 2001*a*) and examines four possible interfaces for dialing a hands-free cell phone, varying the modality of the dialing input (manual vs. voice) and the number of actions needed to dial ("speed dialing" vs. full dialing). The work involves integrating behavioral models for each possible dialing interface with a behavioral model for the primary task of driving. The integrated model is used to predict and examine the effects of cell-phone dialing on various aspects of driver performance.

The dialing and driver models, as well as the final integrated model, are implemented in the ACT-R cognitive architecture (Anderson & Lebiere, 1998). ACT-R, a "production-system" architecture based on condition–action procedural rules and declarative memory elements, has been applied in numerous domains to model human cognition and behavior (see Anderson & Lebiere, 1998). For the purposes of this paper, ACT-R offers three major benefits. First, there is already an existing ACT-R driver model that navigates in a simulated highway environment with traffic (Salvucci, Boer & Liu, in press). The driver model has been shown to replicate various aspects of the driver's control and monitoring behavior during lane keeping, curve negotiation, and lane changing. This model thus serves as an excellent basis for our primary-task model of driving. Second, ACT-R incorporates built-in perceptual-motor modules (ACT-R/PM: Byrne, 2001; Byrne & Anderson, 1998; EMMA: Salvucci, 2001*b*) that facilitate *a priori* predictions concerning performance in the cell-phone dialing task. While ACT-R has no particular modules specific to phone dialing, existing aspects of the perceptual-motor modules carry over to this domain in a straight-forward way; for instance, ACT-R's parameters for typing on a numeric keypad carry over (with minor modifications) to dialing on a standard phone keypad. Third, ACT-R models for different domains can be easily integrated to create models that perform both tasks together, and the architecture subsequently makes predictions about the cognitive and perceptual-motor interactions that arise in performing both tasks. These benefits make ACT-R an excellent framework in which to validate the proposed approach and compare the four possible interfaces for cell-phone dialing.

2. Background: cell-phone dialing and driving

There have been a number of studies examining the use of cell phones while driving, primarily focusing on the effects of conversation or conversation-like tasks. Cell-phone use has been found to have adverse effects on a driver's ability to maintain lane-keeping stability (e.g. Brookhuis *et al*., 1991; McKnight & McKnight, 1993; Serafin *et al*., 1993*a*, *b*; Alm & Nilsson, 1994; Reed & Green, 1999). Cell-phone use also affects a driver's ability to react to environmental situations, such as when a lead vehicle brakes during car following (Brookhuis, de Waard & Mulder, 1994; Alm & Nilsson, 1995). The effects of cell-phone use become even more critical for elderly drivers (e.g. McKnight & McKnight, 1993; Serafin *et al*., 1993*a*, *b*; Alm & Nilsson, 1995). In addition, it has been reported that the risk of collision when using a cell-phone is four times greater than when not using a cell-phone, an increase similar to that observed for drivers with a blood alcohol level at the legal limit (Redelmeier & Tibshirani, 1997). The studies differ on the effects of hands-free vs. hand-held cell phones [e.g., hands-free phones led to better control than hand-held phones in Brookhuis *et al.* (1991), but the two groups had the same risk factors in Redelmeier and Tibshirani, (1997)].

Fewer studies have looked at the effects of cell-phone dialing in particular on driver performance. These studies agree that dialing, like the conversational aspects of cell-phone use, has detrimental effects on lane-keeping ability (e.g. Serafin *et al.*, 1993*a*, *b*; Reed & Green, 1999) and the ability to respond to potentially dangerous situations (McKnight & McKnight, 1993). In fact, dialing has been found in at least one study to have greater effects on driver performance than conversation or conversation-like tasks (Serafin *et al.*, 1993*a*, *b*). These effects persist in both driving simulators and in real-world driving (Reed & Green, 1999).

Even fewer studies have investigated the differences in dialing with multiple types of cell-phone dialing interfaces. Of note, Serafin *et al.* (1993*a*, *b*) tested four dialing interfaces that varied according to the input method (manual vs. voice) and the type of display (instrument panel vs. heads-up display). In a driving simulator study, they found that driver performance as measured by lateral position in the lane was significantly affected during cell-phone dialing, and that voice input led to better performance than manual input. They also found some effects of input method on the total dialing time—namely that manual dialing required more time than voice dialing—but the effect arose primarily from a particular age group and phone-number length (older drivers dialing 11-digit numbers). However, they found no effects of display type on either driver performance or dialing time—that is, both an instrument panel and a heads-up display were equally effective.

This paper extends these previous studies of cell-phone use in several ways. First, it examines a variety of possible dialing interfaces with manual or voice dialing (like Serafin *et al.*, 1993*a*, *b*) and with full or speed number entries (unlike Serafin *et al.*). Second, the paper not only analyses the effects of dialing on driver performance, but also compares total dialing time both while driving and in the absence of driving. Third and most importantly, it utilizes the empirical study to validate a predictive tool that allows for an *a priori* comparison of in-car interfaces using a cognitive architecture.

3. Cell-phone dialing interfaces

The cell-phone interfaces tested and compared in this paper are derived from a basic hands-free cell phone with a standard phone keypad. While today's cell phones are typically small, hand-held devices, cell-phone companies and legislators are beginning to encourage drivers to mount phones in a fixed position inside the car for hands-free use. In addition, some cars today incorporate built-in interfaces for cell-phone calling in addition to other features such as electronic mail reading or Internet access. For the purposes of this paper, hands-free cell phones have the added benefit that we can ignore additional modeling issues that arise from hand-held use (e.g. picking up the phone and dialing with the thumb). For its keypad layout, the basic interface uses the phone keypad shown in Figure 1. The keypad includes a standard numeric layout along with two

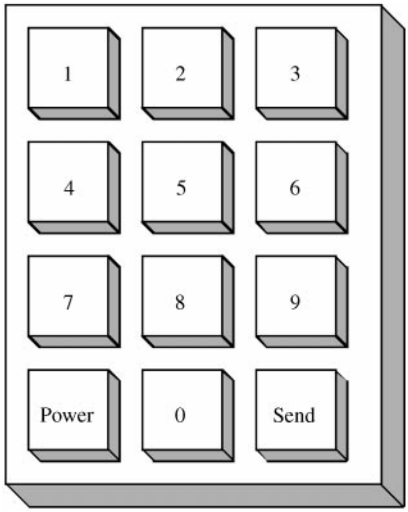


FIGURE 1. Phone keypad used for the dialing interfaces.

special buttons: **Power**, which activates the phone and makes it ready for input; and **Send**, which transmits the dialed number and initiates the call for manual dialing (described shortly).

Four dialing interfaces were designed, varying in two features. First, the interface could involve either manual dialing by pressing keys on the phone or voice dialing by speaking into the phone. Second, the interface could require entering of either the full phone number or a shorter speed code that represents some full number. Combinations of these features led to four possible dialing interfaces that can be characterized as follows.

(1) *Full-manual*: press **Power**, press each number in the desired party's full number (e.g. "555–1234"), and press **Send**.
(2) *Speed-manual*: press **Power**, press the "speed number" associated with the desired party (e.g. "2" for calling "Mom"), and press **Send**.
(3) *Full-voice*: press **Power**, speak the desired party's full number (e.g. "555–1234"), confirm voice recognition by listening to the phone repeat back the full number, and confirm initiation of the call when the phone says "Connecting $\cdots$".
(4) *Speed-voice*: press **Power**, speak the "speed phrase" associated with the desired party (e.g. "Mom"), confirm voice recognition by listening to the phone repeat back the phrase, and confirm initiation of the call when the phone says "Connecting $\cdots$".

All four interfaces require the user to activate the phone by pressing the **Power** button. The manual interfaces then follow the typical procedure for manual dialing in which the user enters either the full or speed number followed by the **Send** button. Likewise, the voice interfaces follow the typical procedure of repeating the recognized number or phrase back to the user to confirm the accuracy of the speech recognition. Note that also like typical phones today, the voice interfaces do not require the user to press **Send** but rather connect soon after confirmation.

Before embarking on the modeling and comparison of these four dialing interfaces, it is worthwhile to highlight the differences among the interfaces. First, we expect the "full" dialing interfaces to require significantly more time than the speed dialing interfaces in terms of the total time to complete the dialing sequence. However, while the total time may give some indication of the effectiveness of the interface, the primary concern is the avoidance of driver distraction and adverse effects on driver performance, and it is not clear that the total dialing time necessarily correlates well with this metric. Second, the manual dialing and voice dialing interfaces clearly occupy different perceptual and motor processes: manual dialing requires manual motor execution and (possibly) visual attention to the keypad, while voice dialing requires speech execution and aural attention to the repeated numbers (for confirmation). Again, it is not obvious as to how these modalities trade off in the presence of a critical primary task such as driving. The modeling approach presented here offers a more rigorous way to take into account these various factors and provide quantitative bases for comparison.

4. An integrated model of cell-phone dialing and driving

Given the four proposed dialing interfaces, we wish to compare the interfaces by constructing an integrated behavior model that can perform both the dialing and driving tasks together. As mentioned, the ACT-R cognitive architecture (Anderson & Lebiere, 1998) is the basic framework in which the models are implemented. Within the ACT-R framework, the existing model of driver behavior (Salvucci *et al.*, in press) is combined with models of behavior in each dialing interface to form the desired integrated model. This section outlines relevant details of the ACT-R architecture as well as specifications of the dialing models, the driver model, and the final integrated model.

4.1. THE ACT-R COGNITIVE ARCHITECTURE

The ACT-R cognitive architecture (Anderson & Lebiere, 1998) is a "production-system" architecture that has been applied to numerous domains including list memory, decision-making, analogy, and scientific discovery (see Anderson & Lebiere, 1998, for a review). As outlined earlier, ACT-R offers a powerful framework in which to implement the behavioral models for dialing as well as for driving. This very brief exposition provides an overview of the architecture for the purposes of understanding the proposed approach to predicting the effects of interfaces on driver behavior; interested readers can refer to Anderson and Lebiere (1998) for a more in-depth treatment of the architecture.

ACT-R posits two basic types of knowledge, declarative and procedural. Declarative knowledge comprises a set of individual units of factual knowledge called *chunks*. For instance, a chunk may represent the fact that $2 + 3 = 5$ or that Boston is the capital of Massachusetts. For driving, chunks may represent numerous types of knowledge such as situation awareness (e.g. "there is a car to my left"), navigational knowledge (e.g. "Broad St. intersects Main St."), or driver goals and intentions (e.g. "stop for gas at the next traffic light"). Procedural knowledge encodes the processes and skills necessary to achieve a given goal. Procedural knowledge comprises a set of *production rules*, condition–action rules that "fire" when the conditions are satisfied and execute the specified actions. The conditions always depend on the current goal to be achieved, and can also depend on the state of declarative knowledge (i.e. recall of a chunk) and/or the current sensory input from the external environment. Similarly, the actions can alter the state of declarative memory (including creating, pushing and popping goals and subgoals) or can initiate motor actions in the external environment.

Given the specification of declarative and procedural knowledge of a model, ACT-R runs the model in simulation and interacts with the external world through its perceptual and motor modules (ACT-R/PM: Byrne, 2001; Byrne & Anderson, 1998; EMMA: Salvucci, 2001*b*). In simulation the architecture generates behavior according to various performance parameters; these parameters describe the time and possible errors involved in both cognitive processes (e.g. chunk recall) and perceptual-motor processes (e.g. encoding a visual object or pressing a key on a keypad). In addition, the architecture provides learning mechanisms for tuning parameter values with experience; for instance, declarative chunks can increase or decrease in activation, and procedural rules can increase or decrease in strength, depending on when and how often they are used. An ACT-R model simulation typically generates a behavioral protocol identical or analogous to a behavioral protocol collected from a human subject. Thus, ACT-R generally allows for straight-forward and detailed comparisons between the predicted behavior of a model and the observed behavior of human subjects.

It is worthwhile to emphasize the two most important aspects of ACT-R for the endeavor of comparing in-car interfaces. First, each ACT-R production rule is specific to a particular goal, and thus a single goal (or subgoal) has a set of production rules associated with it. This aspect of the architecture facilitates a straight-forward integration of multiple ACT-R models: a practitioner can simply combine the rule sets from the various models and then modify the resulting model to utilize each set of rules. Second, while the architecture incorporates numerous parameters that are sometimes estimated for fitting model predictions to data, these parameters all have default values that have been found to serve well for most general purposes; for instance, the architecture provides default values for the rate of chunk activation decay and the time needed to move a hand or type a key. This aspect allows for *a priori* predictions of behavior without relying on parameter estimation from existing data.

4.2. THE DRIVER MODEL

The foundation of the integrated model is the model of driver behavior. For this purpose, we employ an existing ACT-R driver model (Salvucci *et al*., in press) that navigates a simulated highway environment with traffic. The driver model emphasizes three aspects of driver behavior: control of the vehicle, including both lateral control (i.e. steering) and longitudinal control (i.e. speed regulation); monitoring of the external environment, including the roadway and other vehicles, to maintain situation awareness; and decision-making as is needed for lane changes and similar higher-level, discrete decisions. [For a comparison, see also Aasman (1995), for a driver model implemented in the Soar cognitive architecture.] While we might expect that in-car interface use could affect all three of these driver subtasks, this paper stresses the effects of interface use on vehicle control in particular.

The control aspects of the driver model can be described briefly as follows. The model iteratively runs through a two-step cycle in which it perceives relevant aspects of the roadway and then updates control parameters accordingly. For perception, the model encodes two salient points on the roadway: a *near point* in the center of the lane immediately in front of the vehicle, and a *far point* at some distance away from the vehicle (typically at approximately 2–4 s of time headway). The far point can actually be one of several salient visual features, including roadway features such as the road's "vanishing point" or "tangent point" (see, e.g. Land & Lee, 1994) and a lead vehicle directly in front of the driver (i.e. during car following). Given these two points, the driver model calculates the desired update of the steering-wheel angle based on the position and velocity of the near point and the velocity of the far point. Thus, the model in essence uses a "two-level" control model of steering (see Donges, 1978): the near point helps in maintaining a central position in the current lane, and the far point helps in maintaining stability based on upcoming aspects of the road. Salvucci *et al.* (in press) provide a full description of the driver model and an empirical validation of its behavior in a highway environment, including vehicle control as well as monitoring and decision making.

The most critical aspect of the driver model for the purposes of this paper is the method of discrete updating by which it controls the vehicle. Most existing models of driver behavior (and vehicle control in particular) utilize control equations or processes to update steering and speed in a continuous manner (e.g. Godthelp, 1986; Hess & Modjtahedzadeh, 1990). Many of these models also assume that salient perceptual variables (or even more complex variables such as roadway curvature) are readily available to these control systems with no effort, thus implicitly serving better as engineering models of vehicle control rather than human-like models of driver behavior. In contrast, perception and control in the ACT-R driver model occur in discrete steps and each requires time as dictated by the ACT-R architecture. The ACT-R driver model thus does not produce optimal performance; instead its performance depends on how quickly it can perceive the environment and update control. This aspect of the model is critical for our final integrated model: the incorporation of the cell-phone dialing models may affect the frequency of these updates and thus may adversely affect the ability of the model to accurately control the vehicle.

The full environment in which the driver model navigates is a simulated four-lane highway with moderate traffic in both directions. There are two versions of this environment: a minimal-graphics environment that interacts directly with the ACT-R driver model and communicates with the ACT-R perceptual modules as necessary; and a full-graphics environment that allows for real-time replay in the Cambridge Basic Research driving simulator (see Beusmans & Rensink, 1995). Given multiple lanes and other vehicles, the full highway environment is overly complex for the purposes of evaluating the methodology presented here: the many possible interactions between the driver model and the other vehicles on a complex, curvy highway would make it difficult to isolate the effects of cell-phone use as desired here. For this reason the environment was reduced to include a single one-lane straight road that the model navigated at a constant speed. Thus, the critical aspect of driver performance analysed here is the model's ability to control steering and maintain a central position in the lane.

4.3. THE CELL-PHONE DIALING MODELS

The ACT-R models of dialing for each of the tested interfaces are derived from a straightforward task analysis of each interface. The dialing procedures for the interfaces (as illustrated in Table 1) specify the necessary actions for completing a dialing sequence; however, they do not explicitly specify the cognitive, perceptual, or motor processes involved in dialing. Fortunately, a reasonable understanding of these processes arises directly from the task analysis. With respect to cognitive processes, each interface requires the recall of a full phone number or a speed number or phrase. Because theories of list memory and learning suggest that people memorize lists of numbers in smaller chunks (e.g. Anderson, Bothell, Lebiere & Matessa, 1998), the full-dialing models assume that a full seven-digit number is recalled in chunks of 3, 2, and 2 numbers (e.g. "555-1212" as "555" + "12" + "12"). The cognitive processes also handle the step-by-step execution of the models' control flow; these assume that a user has already learned and practiced using the dialing interfaces so that all necessary cognitive procedures are already in place.

TABLE 1

Dialing models for the four tested interfaces. Each line describes an ACT-R production rule in the actual model. Lines marked (†) represent rules that return control to the main driving goal after firing

Full-manual interface Recall phone number Move hand to phone (†) Attend to phone Press **Power** (†) Attend to phone Recall block of numbers Press digit (*repeat until last number*) Press last digit (†) (*repeat until last block*) Press **Send** (†) Move hand to wheel (†)	*Full-voice interface* Recall phone number Move hand to phone (†) Attend to phone Press **Power** (†) Move hand to wheel (†) Recall block of numbers Say digit (†) (*repeat until last number*) Say last digit (†) (*repeat until last block*) Recall block of numbers Listen for number (†) (*repeat until last number*) Listen for last number (†) (*repeat until last block*) Listen for "Connecting…" (†)
Speed-manual interface Recall speed number Move hand to phone (†) Attend to phone Press **Power** (†) Attend to phone Press speed number Press **Send** (†) Move hand to wheel (†)	*Speed-voice interface* Move hand to phone (†) Attend to phone Press **Power** (†) Move hand to wheel (†) Say name (†) Listen for name (†) Listen for "Connecting…" (†)

With respect to perceptual and motor processes, the models interact with the external environment through ACT-R's simulated speech, hands, eyes and ears. [See Ritter (2000), for a similar ACT-R model with simulated eyes and hands that dials an on-screen phone keypad.] The manual interfaces require visual attention to the keypad and a manual execution to press the keys. The manual-dialing models assume that drivers shift their visual attention to the keypad before dialing (which in turn may cause an eye movement to the keypad); while drivers may develop a "blind touch" for the keypad with practice, the models do not currently include this ability. The manual-dialing models also move the right hand to the keypad at the start of dialing and move it back to the steering wheel after the completion of dialing. For typing, the models incorporate all the standard ACT-R parameters for typing on a standard numeric keypad (see Byrne & Anderson, 1998). The voice-dialing models speak the name or number of the desired party through the standard ACT-R speech module (Byrne & Anderson, 1998). They then listen to the phone repeat back the recognized speech signal and compare this signal to the desired name or number; the full-voice assumes that the voice interface repeats one number back every 300 ms.

Table 1 outlines the dialing models for each interface, combining the basic dialing procedures with the cognitive and perceptual-motor aspects described above. Each line in the table represents a single ACT-R production rule whose conditions are met at the given point in the procedure, thus performing the specified actions. The (†) indications in the table mark the points at which the model cedes control to the driver model, as described in the following section.

4.4. THE INTEGRATED MODEL

The integrated model incorporates both the driver model and dialing models in order to perform both driving and dialing together. As mentioned earlier, the integration of multiple models in the ACT-R architecture requires two steps: the combination of the procedural and declarative knowledge sets from each model, and the modification of the procedural rules to allow for an interleaved execution of the two models. The combination of knowledge sets is reasonably straight-forward. The driver model implements a top-level goal called *drive-car*, and the dialing models implement the goals of *dial-full-manual*, *dial-speed-manual*, *dial-full-voice* and *dial-speed-voice*; in other words, when one of these goals becomes the current goal, the rules for these models handle the execution of the given task. Thus, each model implements a distinct goal and the integrated model can simply incorporate the union of the models' rule sets.

The second step of integration, namely the modification of the rules for interleaved execution, requires additional thought. ACT-R does not provide automatic mechanisms for interleaving multiple task models, and so the integrated model must explicitly transfer control between the driving subgoal and the current dialing subgoal (if any). During normal driving without dialing, the integrated model simply runs through iterative control cycles of the *drive-car* subgoal (where a cycle includes perception and a single update of control). When the model generates a new subgoal for dialing the cell phone using a chosen method, it stores the dialing subgoal in the main driving goal and occasionally cedes control to the dialing subgoal. Specifically, the driver subgoal cedes control to the dialing subgoal with a probability of 0.5 (set arbitrarily) after each control cycle. This somewhat naive multitasking scheme is not as rich as that in Aasman and Michon's (1992) Soar driver model in which task management is represented and solved like all other problems in the Soar problem space. Nevertheless, as will become clearer in upcoming sections, the basic multitasking scheme used here is sufficient for an initial attempt at predicting the effects of secondary tasks on driving.

When the driving goal cedes control to the dialing goal, vehicle control is temporarily suspended while the secondary task proceeds. The integrated model thus requires a means by which the dialing goals can return control to the driving goal after some incremental execution. To avoid an arbitrary specification of when this may occur, the integrated model follows a particular parsimonious strategy: the dialing goals cede control when they initiate a perceptual or motor action that requires additional time to complete after the rule actually fires. For instance, when the models need to move a hand or say a number, the ACT-R rule initiates the action by sending the command to the motor or speech module; the action actually completes at some later time, and the subsequent rules may pause until such actions terminate. Also, when the models need to listen to and confirm a number or phrase, the rule initiates the aural encoding of the sound and this encoding completes at some later time. (Note that when the models shift visual attention to a location, only the position of the object is needed rather than a full encoding, and thus these rules require no additional time after rule firing.) Table 1 includes the marking (†) for rules that, after firing and initiating the specified actions, return the control back to the driving goal.

4.5. PARAMETER SETTINGS

In following with our goal of making *a priori* predictions of driver behavior while dialing cell phones, parameters for the integrated model were set as systematically as possible without fitting predictions to observed data. To this end, the integrated model parameters were initially given all its parameter settings from the original driver model; thus the dialing components of the integrated model inherited these parameter settings as well. After some exploratory model simulations to observe the general behavior of the model, two aspects of model behavior suggested slight modifications to the initial settings. First, the model sometimes ceded control to the dialing task even when the vehicle became unstable—that is, its lateral velocity in the lane became greater than would be comfortable for a human driver. This motivated a modification such that the integrated model would delay secondary-task use in critical or dangerous situations; specifically, the model was modified such that the driving goal only cedes control when the near and far points are relatively stable, computed as whether their combined angular velocity is less than a given threshold (set at 2.3°/s after exploratory testing). Second, while the driver model closely followed the lane center in the full highway environment, lane centering was less critical here for the more minimal one-lane environment. This motivated a modification in which the driver model parameter that controls the aggressiveness of lane centering was halved from its original value. These two modifications did not represent a "tweaking" of quantitative parameter values in light of the observed data but rather represent an attempt at improving the model through more rigorous and accurate task analysis.

5. Integrated model predictions

The integrated model of driving and cell-phone dialing enables us to generate predicted behavior for driving while dialing each of the four cell-phone interfaces. This section describes the process by which these predictions are generated through model simulations in the driving environment. It also discusses the model's predictions with respect to the effects of dialing on driver performance and also the effects of driving on dialing times in the four interfaces.

5.1. GENERATING MODEL PREDICTIONS

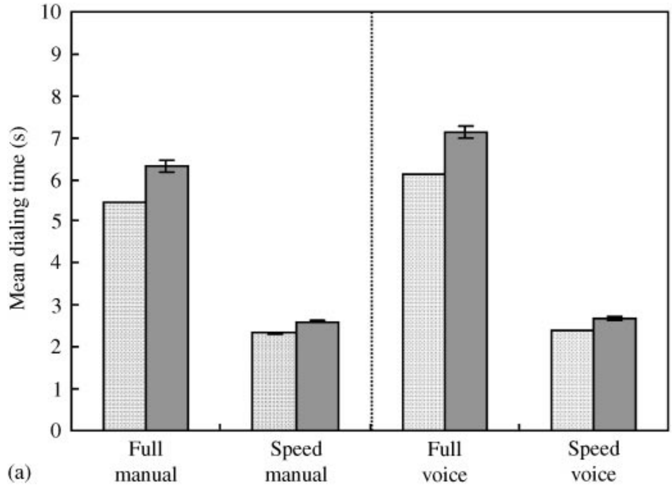
The integrated model generates predictions by driving in the model's simulated one-lane road environment (described earlier), producing a behavioral protocol that records its behavior for analysis. The present study involves three simulation runs of the model driving in the environment at a constant speed of 60 mph. Starting at a standstill in the center of the lane, each simulation began with the model accelerating up to its constant speed. After 20 s the model was given the secondary-task goal of dialing the cell phone using one of the four dialing interfaces. When the dialing task was completed, the model resumed normal driving for another 20 s and repeated another dialing task. This process continued until the model had completed eight dialing sequences for each interface for a total of 32 dialing sequences. These three simulation runs thus provided data for driving while dialing as well as normal driving without dialing. In addition, the study included three simulation runs where the model simply dialed the cell phone without a primary driving task. Again each simulation run comprised eight dialing sequences for each interface for a total of 32 dialing sequences.

5.2. DIALING TIME PREDICTIONS

This first analysis examines the average *dialing time*, that is, the total time needed to complete a dialing sequence. The two sets of simulations allow us to examine separately the "baseline" dialing times without driving and the dialing times during driving. Figure 2(a) shows the average dialing times for each of the four dialing interfaces. The dialing times while driving were all higher than those in the baseline condition (normal driving). It may be somewhat surprising that these differences were not larger, with a maximum difference of only about 1 s, indicating a relatively small effect of driving on the total dialing time. Overall, full dialing required more time than speed dialing. Full-voice dialing required more time than full-manual but speed-voice and speed-manual required approximately the same time.

5.3. LATERAL POSITION PREDICTIONS

While the dialing time predictions give some indication of behavior in the interfaces in terms of the total time, such a measure is not necessarily an indication of how the interfaces affect driver performance. Given the chosen one-lane road environment, driver performance can be characterized as the ability to keep the lateral position of the car centered in the lane. Lateral positions were analysed during periods of normal driving and during the use of each of the four dialing interfaces. Because cell-phone dialing can



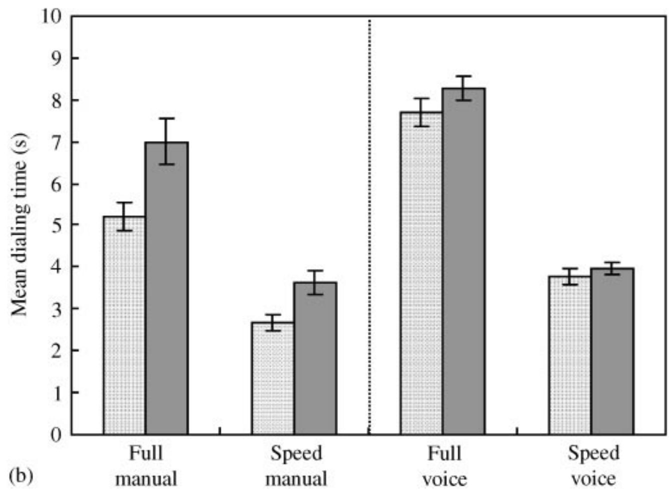


FIGURE 2. Average dialing time for each interface while not driving (baseline) and while driving for (a) the integrated model and (b) the empirical data. The error bars represent standard errors: ▢, baseline; ■, driving.

affect driver performance both during and immediately after dialing, the following lateral position results include 5 s of data after the completion of dialing, which approximates the amount of time needed to make a centering corrective maneuver during lane keeping (Hildreth, Beusmans, Boer & Royden, 2000).

One possible measure of lateral position is *lateral deviation*, defined as the root-mean-squared error between the actual lateral position and the center of the lane. Figure 3(a) shows the model's predictions of lateral deviations during normal driving and while using each dialing interface. Like human drivers, the model does not keep the vehicle perfectly centered even during normal driving, exhibiting lateral deviations of approximately 0.15 m. The model exhibits various effects across the dialing conditions. Full-manual dialing clearly had the largest effect on lateral deviation. The speed-manual

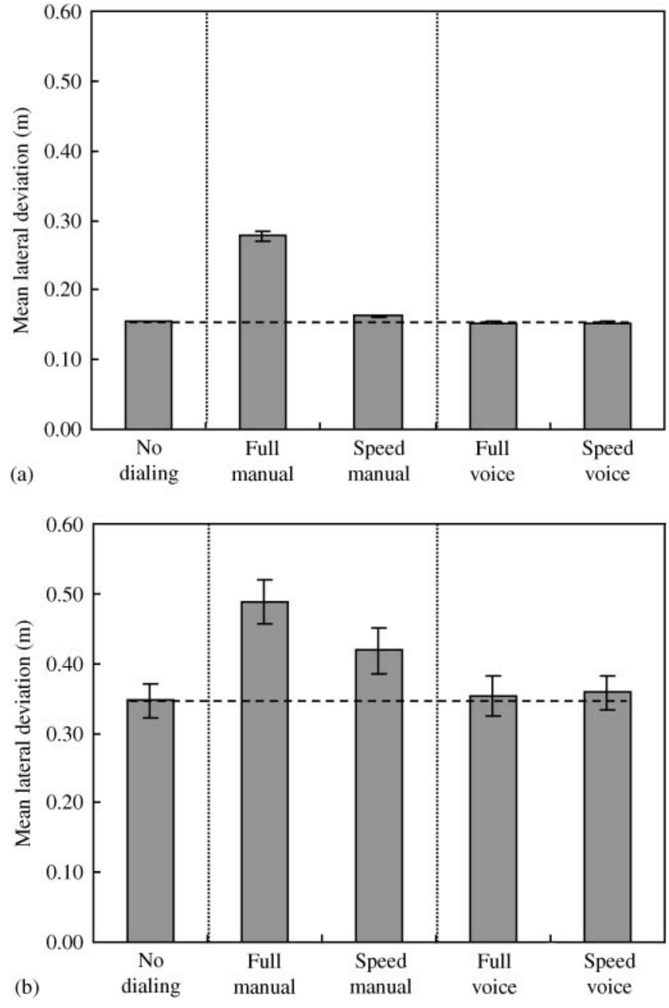


FIGURE 3. Average lateral deviation without dialing and while dialing each interface for (a) the integrated model and (b) the empirical data. The error bars represent standard errors.

deviations were significantly smaller than the full-manual deviations, $t(4) = 14.64$, $p < 0.001$, but were also larger than the deviations for normal driving, $t(4) = 5.79$, $p < 0.01$, and both full-voice and speed-voice dialing, $t(4) = 5.30$ and $t(4) = 5.37$, $p < 0.01$. There were no significant differences among normal driving, full-voice dialing, and speed-voice dialing, $p > 0.05$.

A related measure, *lateral velocity*, represents the change in lateral position and thus the stability (or instability) of the vehicle in the lane. Figure 4(a) shows the average lateral velocities for normal driving and while dialing in the interfaces. The effects with respect to lateral velocity were analogous to those with respect to lateral deviation. The full-manual velocities were significantly larger than those for all conditions, $p < 0.05$. The speed-manual velocities showed significant differences from the velocities for normal

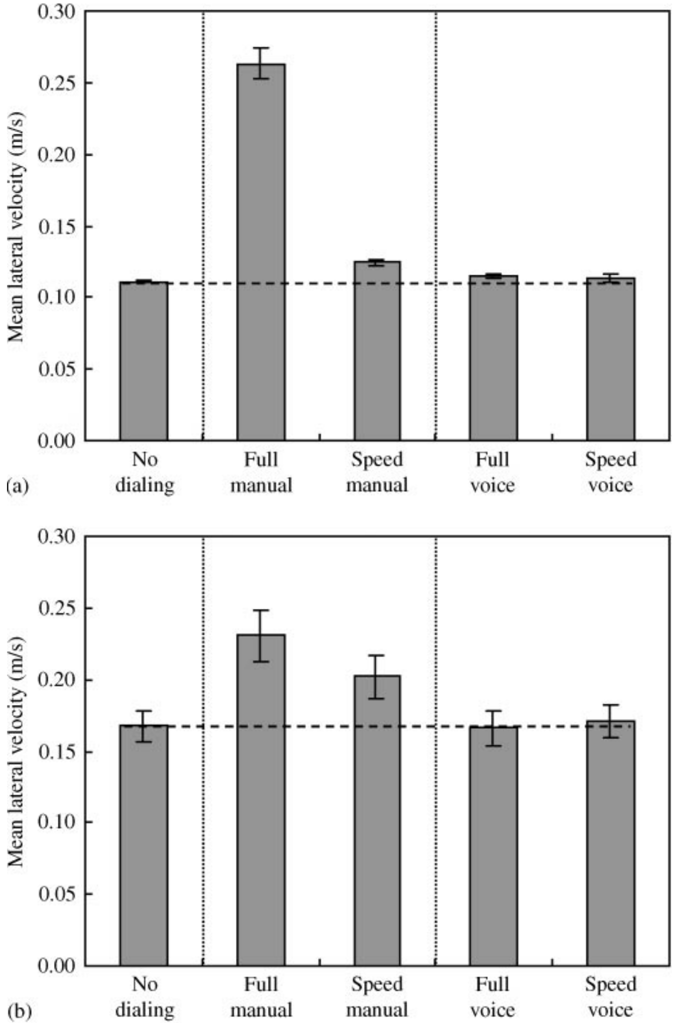


FIGURE 4. Average lateral velocity without dialing and while dialing each interface for (a) the integrated model and (b) the empirical data. The error bars represent standard errors.

driving, $t(4) = 6.64$, $p < 0.01$, full-voice dialing, $t(4) = 3.85$, $p < 0.05$, and speed-voice dialing, $t(4) = 3.56$, $p < 0.05$. Again there were no differences among the normal driving and voice dialing conditions, $p > 0.05$.

5.4. SUMMARY OF MODEL PREDICTIONS

The integrated model made several interesting predictions about the effects of driving on dialing and the effects of dialing on driving. The model predicted that dialing times would increase significantly while driving, but not by a large amount (up to approximately 1 s). It also predicted, according to baseline times, that the full-voice dialing interface would require the most total time and the speed-dialing interfaces would require the least time. With respect to the lateral position, the model predicted that the full-manual interface would have large effects on driver performance, the speed-manual interface would have small but significant effects, and the voice interfaces would have no effect.

An examination of the model's behavior while using the various dialing interfaces offers an indication of why these predictions came about. The manual interfaces both require multiple shifts of visual attention to the cell phone, whereas the voice interfaces only shift attention once before the first hand movement to the phone. Because the model also requires visual attention during driving to perceive the road, the extensive use of visual attention in the manual interfaces leads to more conflicts for visual attention, which in turn leads to greater time being spent in shifting attention (and the eyes) between the cell phone and the roadway. This struggle for visual attention is the primary bottleneck between the integrated model's driving and dialing goals and is the primary cause of the reduced performance of the manual interfaces. The voice interfaces, because they utilize modalities not used for driving (i.e. speech and aural attention), avoid such conflicts and have no significant effects on driver performance. These predictions are consistent with the general findings of task interference with multiple tasks competing for the same resource(s) (e.g. Pashler, 1994). It should be emphasized that the interactions and potential conflicts between modalities is an important benefit of implementing the integrated model in a cognitive architecture: the integrated model does not explicitly specify these interactions, but rather they arise from the dialing and driving goals' use of shared resources and the architecture's quantitative predictions about how this use may sometimes lead to conflicts and reduced performance in the primary task.

6. Empirical validation

Given the predictions of the integrated model, an empirical study was conducted to compare the model's behavior with that of human drivers dialing cell phones. The primary goal of the study was to collect data from human drivers in an environment and task as similar as possible to the environment and task given to the model. To this end, the study involved an experiment in which participants drove in a fixed-base driving simulator on the same one-lane roadway and at the same speed. The resulting data allowed for an analysis of driver behavior and a comparison with model predictions with respect to the same measures examined for the model, namely dialing time and lateral position.

6.1 METHOD

6.1.1. Participants. Sixteen drivers in all participated in the experiment. Four of these drivers had only 2 years or less of driving experience and were omitted from further analysis. An additional driver exhibited inexplicably erratic driving with outlier behavior and was also omitted. The 11 remaining drivers—five women and six men—ranged in age from 19 to 32 with an average age of 25. Of these 11 drivers, three use a cell phone regularly (at least a few times per week), and all three have used a cell phone while driving. In addition, of the eight who do not use a cell phone regularly, four have used a cell phone at some point while driving.

6.1.2. Environment and task. In the experiment, drivers navigated a one-lane roadway in the Nissan CBR fixed-base driving simulator (see Beusmans & Rensink, 1995). The simulator uses the front-end of a Nissan 240SX that has been instrumented to collect all the typical vehicle control data, such as steering wheel angle and accelerator/brake pedal positions. The instrumented vehicle communicates with a Silicon Graphics workstation that generates the simulated environment and maps the input control signals into the proper vehicle dynamics (including sound). The simulated environment display is projected in front of the vehicle, providing a field of view of approximately 70° in front of the driver. The display includes a textured roadway 3.66 m wide (the standard American lane width) and walls extending 2.75 m from the road boundaries. A standard phone keypad was mounted on the inside of the vehicle's center console within easy reach of the driver; the exact location of cell-phone mounting has been found to have no significant effects on either dialing or driving behavior (Serafin *et al*., 1993*a*, *b*).

The driving task given to human drivers was identical to that given in the integrated model. Drivers navigated a one-lane roadway at a constant speed of 27.6 m/s (61.7 mph) as maintained by the simulator, and thus drivers only needed to handle the steering aspects of vehicle control. At intervals of 20 s, the experimenter asked the driver to call a certain party on the cell phone; the dialed party came from one of the four parties designated by the driver before the experiment as familiar phone numbers. For the voice interfaces, the experimenter acted as a surrogate voice recognition system and repeated the driver's input back to the driver. Like the model, drivers performed eight dialing sequences in each interface for a total of 32 dialing sequences. The sequences for each interface were blocked together, and the order of blocks was counterbalanced across drivers. The drivers were also asked before and after the experiment to perform dialing sequences in the absence of driving for a total of 32 dialing sequences equally distributed between the start and end of the experiment and among the four interfaces.

6.1.3. Procedure. After being introduced to the task and driving simulator, the participant entered the simulator and drove until s/he felt comfortable. At this point the participant performed the first set of dialing sequences without driving. The participant then began the main portion of the experiment, driving down the one-lane road at a speed of approximately 60 mph and being asked to dial the phone at 20 s intervals. This main portion consisted of four blocks—one for each dialing interface—and before each block the participant was told to utilize a particular interface and was reminded about the procedure for the interface. Upon the completion of driving, the participant performed the last set of dialing sequences without driving.

6.2. DIALING TIME RESULTS

The dialing time results for the human drivers are shown in Figure 2(b). As for the model, there were a number of significant effects and interactions. A repeated-measures analysis of variance (ANOVA) was conducted for these results along three factors: task (baseline vs. driving), modality (manual vs. voice), and input length (full vs. speed). The drivers exhibited significant main effects of task, $F(1,10) = 21.62$, $p < 0.001$, modality, $F(1,10) = 57.88$, $p < 0.001$, and input length, $F(1,10) = 153.90$, $p < 0.001$. These effects were analogous to those for the model: driving dialing times exceeded baseline times, voice-dialing times exceeded manual-dialing times, and full-dialing times exceeded speed-dialing times. The category factor showed significant interactions with modality, $F(1,10) = 19.25$, $p < 0.01$ and length, $F(1,10) = 11.01$, $p < 0.01$; the full-manual interface had the largest difference between driving and baseline conditions whereas the speed-voice interface had the smallest difference. The interaction between modality and length was also significant, $F(1,10) = 10.73$, $p < 0.01$, due to increased differences between full and speed dialing for the manual and voice interfaces. The three-way interaction was not significant, $p > 0.10$.

When comparing the empirical results to the model predictions in Figure 2(a), the human drivers, like the model, exhibited relatively small increases in dialing time while driving over baseline conditions. However, the range of differences between driving and baseline was larger for human drivers: the difference reached almost 2 s for full-manual dialing, while the difference was not significant for speed-voice dialing, $p > 0.10$. While the differences for the model were primarily a function of total dialing time (greater differences of longer dialing times), the differences for the human drivers were also a function of modality (greater differences for manual dialing). Nevertheless, the model's overall pattern of predictions closely correlated with the drivers' overall pattern of behavior, $R = 0.95$.

6.3 LATERAL POSITION RESULTS

Figure 3(b) shows the lateral deviation results for the human drivers. The pair-wise comparisons show that the full-manual lane deviations were larger than the speed-manual lane deviations, although the difference was not significant, $t(10) = 1.78$, $p > 0.10$. The speed-manual deviations were marginally significantly different than the full-voice and speed-voice deviations, $t(10) = 2.14$ and $t(10) = 1.86$, $p < 0.10$, and significantly different from the normal driving deviations, $t(10) = 2.68$, $p < 0.05$. The full-voice, speed-voice, and normal driving deviations were not significantly different from one another, $p > 0.10$.

Figure 4(b) shows the lateral velocity results for the human drivers. The pair-wise comparisons were similar to those for lateral deviations: full-manual yielded the largest deviations, and for lateral velocity the deviations were marginally significantly different from speed-manual, $t(10) = 2.15$, $p < 0.10$; speed-manual was significantly different from full-voice, speed-voice, and normal driving, $p < 0.05$; and full-voice, speed-voice, and normal driving were not significantly different from one another, $p > 0.10$.

Overall the empirical results in Figures 3(b) and 4(b) corresponded well to the model predictions in Figures 3(a) and 4(a): for lateral deviation, $R = 0.92$, and for lateral velocity, $R = 0.88$. In addition, the pair-wise comparisons for the empirical data suggest an overall picture that is similar to, though not as (statistically) distinct as, that for the integrated model—namely, that full-manual dialing has a large effect on the lateral position measures, speed-manual dialing has a smaller but significant effect, and full-voice and speed-voice dialing have no significant effect. Thus, the model did a reasonably good job in predicting the effects of dialing on driver performance for the two lateral position measures.

Nevertheless, it should be noted that the magnitudes of the model predictions varied greatly from those of the empirical data. The model's lateral deviations were generally about half of those for the human drivers; the model's lateral velocities were closer to the driver lateral velocities but showed a much greater range. This discrepancy in magnitudes is potentially attributable, at least in part, to the differences between driver behavior in a driving simulator and in a real-world vehicle. Researchers have reported finding larger effects of measures such as lateral deviation and lateral velocity for driving simulators as compared to real-world driving. The driver model, in exhibiting smaller effects than the drivers in the study, may potentially be more representative of real-world driving than simulator driving. However, further empirical studies of real-world driving is clearly needed to support this. In any case, although the model was less accurate in predicting the size of the effects, it did manage to predict the qualitative, rank-order trends in the empirical data.

7. General discussion

The integrated-model approach proposed in this paper represents a methodology for comparing in-car interfaces and, more generally, secondary-task interfaces in the presence of a performance-critical primary task. The integrated model of dialing and driving made two main sets of rank-order predictions: (1) the full-manual interface had large significant effects on driver performance, the speed-manual interface had small significant effects, and the voice interfaces had no significant effect; (2) the speed-manual interface required the least time, followed by the speed-voice interface, the full-manual interface, and finally the full-voice interface. The empirical study of human drivers, while not supporting some of the model's quantitative predictions, supported both sets of rank-order predictions with respect to the measures of dialing time and lateral position.

While this study serves well to illustrate the benefits of the proposed approach, it is useful to note two limitations of the study with respect to the tasks employed. First, the driving task, where drivers steered on a single-lane road at a constant velocity without traffic, provided a well-controlled environment in which we could look specifically at the effects of dialing on one aspect of behavior (i.e. steering). However, it is clearly important to extend this work to more complex domains that would better represent real-world driving situations, and our approach is well suited for this extension due to the fact that we have an existing driver model for a complex environment (namely navigating a multi-lane highway with traffic; see Salvucci *et al*., in press). Second, the dialing task used interfaces based on a simple keypad that provided no feedback. The dialing task could be improved by utilizing a commercially available cell phone and its built-in dialing methods, thus, as for the driving task, increasing the realism and validity of the analysis. A new study involving these two extensions is currently underway.

In addition, the study also has limitations with respect to the model, particularly in its ability to account for two important aspects of behavior: individual differences and learning. The most glaring example of learning and differences in the simulator experiment arose in drivers' attempts to alleviate the visual demands of the dialing task. The drivers all generally started out using the prototypical dialing strategies embodied by the model—for instance, looking down at the phone when dialing manually. However, some drivers began to adapt this strategy as they learned the layout of the phone and became more comfortable with the driving task. In particular, a few drivers attempted to dial "by feel" later in the experiment by feeling around the keypad rather than looking. The naïve model presented here does not currently capture the differences between the individual drivers in their desire and/or ability to learn and utilize such strategies.

7.1. PERCEPTUAL-MOTOR CONSIDERATIONS FOR INTEGRATED MODELS

The integrated model approach as presented here makes extensive use of perceptual-motor mechanisms in generating and predicting behavior. The driver model and dialing models rely on two perceptual-motor extensions of the basic ACT-R cognitive architecture, ACT-R/PM (Byrne, 2001; Byrne & Anderson, 1998) and EMMA (Salvucci, 2001*b*). ACT-R/PM incorporates modules for visual attention, aural attention, hand and finger movement, and speech with built-in parameters that specify the temporal and spatial characteristics of these processes (based on the EPIC cognitive architecture of Kieras & Meyer, 1997). EMMA extends ACT-R further with a vision module that dissociates visual attention and eye movements and generates eye movements based on shifts of visual attention as directed by the cognitive processor. Both extensions interact with the minimal driving environment described earlier, thus providing a rigorous interface between the ACT-R cognitive model and the (simulated) task environment.

There are at least three reasons for which the modeling of perceptual-motor processes is critical to the proposed approach. First, the mechanisms increase the plausibility and realism of the model by requiring that it access information through "proper" perceptual channels rather than assuming this information is already encoded somehow in memory. Second, these mechanisms generate a quantitative behavioral protocol that accounts not only for aggregate behavior but also the time-sequenced process in which the behavior unfolds. The behavioral protocol generated by the model is (typically) completely analogous to that generated by human subjects, greatly facilitating an analysis and comparison of model and human behavior. Third, the mechanisms allow the model to account for interactions between the various processes, especially bottlenecks that arise when multiple tasks require the same modality. Each of these issues played a crucial role in our study. The integrated model of driving and dialing accesses its perceptual information through the standard perceptual-motor mechanisms, which in turn predict the time needed to access the information and impact performance of the model. In the simulation, the model generates a behavioral protocol identical in form to those generated by human drivers in the driving simulator, allowing for a direct comparison of the protocols. These comparisons revealed that the most critical aspect of the cell-phone dialing task was the need to shift visual attention to the phone before pressing a key. Because the driving task also requires visual attention, the interaction of the two tasks led to a competition for visual attention and in turn led to a decreased performance for manual dialing. Only by modeling both the cognitive and perceptual-motor aspects of the two tasks could the approach successfully account for these interactions.

7.2. PRACTICAL APPLICATION OF THE INTEGRATED-MODEL APPROACH

Clearly, the integrated model approach has numerous practical applications for real-world domains. For instance, considering the specific application to driving, this paper helps in highlighting an interesting issue for evaluating and comparing in-car interfaces: the relationship between the total time to perform a secondary task and potential effects on driver performance. We might expect that, generally speaking, longer tasks would have a greater potential of affecting driver performance. However, in the present study, the full-voice interface required the most time to complete dialing and yet had no significant effect on performance, whereas the speed-manual interface required the least time and yet had a significant effect on performance. Thus, while the total time may certainly affect driver performance, it is clearly not the only factor involved, and the integrated-model approach facilitates the incorporation of these other factors (e.g. allocation of visual attention) in the comparison of in-car interfaces. Such comparisons can in turn impel a faster evaluation and prototyping of interfaces, particularly in the early stages of development.

An extensive practical application of the approach to driving and in-car interfaces will require more usable tools for designers and practitioners in order to evaluate interfaces quickly and effectively. The ACT-R cognitive architecture employed here is fairly complex with respect to its account of cognition and perceptual-motor behavior, as are related production-system architectures such as EPIC (Kieras & Meyer, 1997) and Soar (Laird *et al*., 1987; Newell, 1990). The sophistication of these architectures allows for more rigorous models but also complicates the modeling effort. In contrast, frameworks such as GOMS (Card *et al*., 1983) provide a less sophisticated functionality but allow for much more rapid prototyping of models for more straight-forward tasks. The domains of dialing and driving nicely illustrate this tradeoff. The driver model requires a sophisticated architecture such as ACT-R to handle the complexity of the domain; simpler frameworks like GOMS, or even extended relatives such as CPM-GOMS (John, 1990), do not have the complexity for adequately modeling driver behavior. In contrast, GOMS or CPM-GOMS (or their relatives) greatly facilitate implementation of the dialing models or models of other secondary-task behavior that may not require the sophistication of ACT-R or a similar architecture. In addition, while the driver model may take many man-hours for design and improvement, models for in-car interfaces would typically need to be developed much more efficiently. Future practical systems for integrated model development could potentially provide tools to implement and integrate models in multiple frameworks depending on the complexity of the task and the time constraints of development.

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