A Cognitive Constraint Model of the Effects of Portable Music-Player Use on Driver Performance

Duncan P. Brumby[1], Dario D. Salvucci[1], Walt Mankowski[1], & Andrew Howes[2]

[1]Department of Computer Science
Drexel University
Philadelphia, PA 19104 USA
{Brumby,Salvucci,Walt}@cs.drexel.edu

[2]Manchester Business School
University of Manchester
Manchester, M15 6PB UK
HowesA@manchester.ac.uk

We describe an approach to modeling strategic variations in how people might select media content from an Apple iPod portable music player while driving. An experiment was conducted to determine the time required to select a target from a list using the scroll wheel on the iPod. It was found that a linear model accurately predicted the time to scroll through a list to a target. This model was then used in conjunction with a previously reported steering control model to derive *a priori* predictions for dual-task performance over the entire range of possible multitasking strategies. From this set of strategies, we then focused on identifying the *fastest* and the *safest* strategies for completing both a simple selection task and also a more complex selection task. It was found that the model predictions bracketed the observed human data from a recent study that investigated the effects of using an iPod while driving. Moreover, the analysis suggests that in order to compensate for the inherent risks of using devices that demand longer interaction episodes to complete a task, people might adjust their multitasking strategy by giving more time up to steering control while completing the secondary task.

INTRODUCTION

People continue at an increasingly alarming rate to perform distracting tasks while driving — for example, a recent study of over 5,000 American drivers found that 40% of all drivers talk on cell phones, 20% of drivers aged 18-24 select songs on an iPod, and 24% of this younger group send text messages, all while driving (2006, GMAC Insurance National Drivers Test). From a human factors standpoint it would be beneficial if the potential effects of using a mobile device while driving could be better understood and predicted.

To this end, researchers have started to use cognitive modeling. One common approach has focused on developing computational models in a cognitive architecture that interface with a virtual reality simulation of a driving environment (e.g., Salvucci, 2006, 2001; Tsimhoni & Liu, 2003). While these models have accounted for many performance measures of human driver behavior under single- and dual-task conditions, these efforts have generally not attempted to explore possible strategic variability in behavior.

In contrast, Brumby, Howes, and Salvucci (2007a) have described a *cognitive constraint model* (CCM, Howes et al., 2007) that explores possible strategic variations in performing a secondary dial task while driving. The CCM approach focuses on understanding the constraints on the interaction between the driver and the task environment and allows for objective functions to represent desired trade-offs in relation to critical performance variables (e.g., trade-offs between task time and driver performance). In some respects, the approach taken by Brumby et al. (2007a) to modeling behavior over the range of possible strategies is similar to Kieras and Meyer's (2000) bracketing heuristic. The bracketing heuristic gives predictions of the speed of the fastest-possible strategy and the slowest-reasonable strategy for a complex task — these brackets are useful because observed performance should always fall somewhere between the performance of these two strategies.

The aim of the current paper is to extend Brumby et al.'s (2007a) previous analysis of the dialing while driving example to a more complex secondary in-car task; namely selecting media content from an Apple iPod portable music player while driving. This is a significant step because an accurate task model for the iPod is lacking in the field. Moreover, the iPod is a popular portable device that is frequently used by the driver of a car, and its use has recently been shown to affect driver performance (Salvucci et al., 2007). In particular, Salvucci et al's study found that selecting media on the iPod had a significant effect on driver performance as measured by lateral deviation from the lane center. In addition, participants in the study were required to make both simple and complex selections of media content while driving. It was found that the complex selection task had more of a deleterious effect on driver performance than the simple selection tasks.

In this paper, we describe an approach to modeling possible strategic variations in how people select media content from an iPod while driving. In order to model the iPod selection task, an experiment was conducted to determine typical timing estimates for scrolling to and selecting an item in a list. This model was then used in conjunction with a previous steering control model (Brumby et al., 2007b) to derive *a priori* predictions for dual-task performance, which were compared to human data.

MODELING THE EFFECTS OF PORTABLE MUSIC-PLAYER USE ON DRIVER PERFORMANCE

Modeling Steering Control

Brumby et al. (2007b) describe a cognitive constraint model of steering control that gives predictions of changes in a vehicle's lateral deviation (i.e., distance from the lane center) over time.

The focus of the model is on how constraints imposed by the environment (e.g., noise affecting the heading of the vehicle over time) and constraints imposed by cognition (e.g., people's sensitivity to the lateral position of the vehicle in relation to the center of the lane) interact to determine driver 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 lateral position in the lane at the time that the steering update is performed. In particular, given the vehicle's lateral deviation, a quadratic function is used to model the mean lateral velocity of the vehicle following the steering update. In some respects this approach is similar to control theoretic accounts of lane keeping (e.g., model 1 in Hildreth et al. 2000), which assume that adjustments to the heading of a vehicle are motivated by the goal of minimizing perceptual input quantities that represent the lateral position and heading of the vehicle.

In order to parameterize the model an analysis of human steering data was conducted by Brumby et al. (2007b). The aim of this analysis was to formally characterize how drivers typically adjust the lateral velocity of a vehicle given its lateral position in the roadway. Brumby et al. assume that adjustments to lateral velocity are motivated by the driver attempting to maintain a central lane position. Brumby et al. segmented steering data collected from a previous study (Salvucci, 2001) into a series of *steering episodes*. A steering episode was defined as a period of time in which the angle of the steering wheel did not alter. For each steering episode, Brumby et al. defined a tuple representing the duration of the episode, the change in the lateral position of the vehicle, and the average lateral velocity of the vehicle.

Regression analysis was conducted to estimate a best fitting curve to predict the average lateral velocity of a steering episode given the lateral deviation *LD* of the vehicle at the start of the episode,

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

It was found that a quadratic function (Eq. 1) provided a high degree of correspondence with the human steering data ($r^2 = 0.61$).

The quadratic model predicts that as the car drifts farther from the lane center, drivers tended to react by making sharper corrective steering movements, which increase the lateral velocity of the vehicle and, as a consequence, return it to a central lane position more rapidly. Furthermore, the intercept of the curve gives some suggestion of the driver's threshold for judging the vehicles deviation from the lane center. When the car is near the lane center (i.e., lateral deviation < 0.30 m), predicted lateral velocity is close to zero. This means that the position of the car in the roadway remains more or less constant over time. This implies that the driver was possibly satisfied with the vehicle's position in the roadway if the lateral deviation of the vehicle was less than 0.3 m from the lane center. Moreover, the model provides a computationally efficient formalism for predicting how drivers typically adjust the heading (or lateral velocity) of a vehicle given its lateral position in the roadway.

Although the quadratic model gave a high degree of correspondence with the human steering data, there was considerable variability with respect to the observed lateral velocities for a given lateral deviation at the start of an episode (*S.D.* = 0.10 m/s). This suggests that people's adjustments to the heading of the vehicle were stochastic. In order to develop a stochastic model, random values were sampled from a Gaussian distribution and added to the value of the updated lateral velocity. Based on an estimate of the average standard deviation observed in the human data, the Gaussian distribution had a mean of 0.00 m/s and standard deviation of 0.10 m/s.

The steering control model assumes that in between steering updates the vehicle continues along its heading, but that it's heading is permuted by noise. This noise represents the fact that, if left unattended by the driver, the heading of a car will be influenced by external factors in the environment (e.g., bumps in the road, wind, the camber of the road, etc). Consistent with Hildreth et al.'s (2000) model, a value from a Gaussian noise was added at a rate of every 50 ms to the lateral velocity of the vehicle determined at the previous update. The Gaussian noise distribution had a mean 0.00 m/s and standard deviation 0.10 m/s.

Finally, it is worth pointing out that we do not make any strong theoretical commitment to the duration of a typical steering update; the model is solely dependent on parameters derived from the analysis of steering performance data. For the purposes of the current analysis we assume that in normal driving conditions steering updates occur at an frequency interval of once every 500 ms. At this baseline interval between steering updates, lateral deviation predictions given by the model (*M* = 0.33 m, *S.D.* = 0.02 m) are comparable with reported baseline lateral deviation (*M* = 0.35 m, *S.D.* = 0.08 m) in Salvucci's (2001) experiment.

Modeling the iPod Selection Task

In order to model the iPod selection task, an experiment was conducted to determine the time required to scroll to and select a given item *i* in an ordered list using the device interface. The study used an Apple iPod (5th-generation video iPod) that was modified to run RockBox, an open source firmware replacement. The RockBox software allowed interaction protocols to be recorded (i.e., button-presses and left and right scrolls). In the study, 10 participants were required to search for a target number within a sorted list (e.g., scroll to and select "15" within the list of numbers 1-200). The position of the target item within the list was varied across trials.

Figure 1 shows the average time for participants to scroll to and select a target located at position *n* in the list. Participants were timed from when they began scrolling (i.e. they moved from line 0 to line 1) until they clicked on the target line. There is a clear linear trend to the data in Figure 1, such that the time required to select a target in the list is proportional to the number items that need to be scrolled through in order to reach the target. Regression analysis was conducted to estimate a best fitting curve. It was found that a linear function (Eq. 2) gave a high degree of correspondence with the human data ($r^2 = 0.996$), $t(35) = 88.81$, $p < .001$.

$$Duration = 0.0714 \text{ x } N\text{-}Items\text{-}Scrolled + 1.44 \quad (2)$$

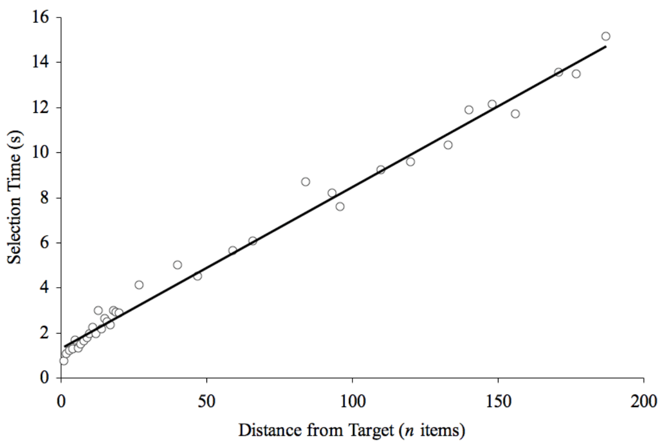

Figure 1: Data plot showing the average time for participants to scroll to and select a target at position *n* in an ordered list on the Apple iPod.

The linear scroll model was used to derive timing predictions for a set of tasks used in a recent study that investigated the effect of iPod interaction on driver performance (Salvucci et al., 2007). In Salvucci et al's study, participants were required to select various media content (e.g., songs, podcasts, and videos) while driving a simulated car down the middle of three-lane highway environment. All media content in the study were arranged in their default menu structure on the Apple iPod. The linear model was used to make detailed *a priori* predictions from a set of task procedures used in the study of the time required to complete each task. These task procedures and the resulting task time predictions are detailed in Table 1. The benefit of using the model is that it allows for detailed predictions of the amount of time taken at each step in the overall task procedure.

Table 1: Procedure and predicted duration for selecting a song, podcast, and video for Salvucci et al. (2007) study.

Selection	Details	Number of Items Scrolled	Modeled Duration
Song	Select "Music"	0	1.4 s
	Select "Artists"	1	1.5 s
	Select target artist A_i	60	5.7 s
	Select target song S_i	5	1.8 s
Podcast	Select "Music"	0	1.4 s
	Select "Podcasts"	4	1.7 s
	Select target podcast P_i	2	1.6 s
Video	Select "Video"	2	1.6 s
	Select "Movies"	1	1.5 s
	Select target movie M_i	2	1.6 s

Modeling Dual-Task Performance

We next use the models of steering control and iPod selection to derive performance predictions for dual-task performance. We focus on accounting for human data reported in a recent study (Salvucci et al., 2007) that investigated the effect of iPod use while driving on task time and lateral deviation.

We assume that one of the consequences for steering control of engaging in a secondary task while driving is that the interval between consecutive steering updates generally increases. Recall that we assumed that in normal driving conditions drivers typically adjust the heading of the vehicle once every 500 ms. We assume that engaging in a secondary task while driving generally disrupts this pattern of checking and adjusting the heading of the vehicle. In particular, we assume that steering updates cannot occur while the driver's attention is directed towards a secondary in-car task, such as when they are engaged in scrolling through a list to locate a target. This assumption is based on the idea that peripheral resources, such as the eyes, will limit the degree of parallel processing between tasks. Moreover there are numerous demonstrations in the literature of central interference affecting driver performance in dual-task conditions (e.g., Brumby, Salvucci, & Howes, submitted; Levy, Pashler, & Boer, 2006).

Furthermore, 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 iPod). 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 iPod and the road, or vice versa. Thus, the benefit to driving performance of frequently interleaving tasks must be traded-off against the cost of switching between tasks.

MODELING EXPERIMENT

Given that cognitive resources are limited, the question addressed here is how tasks should be interleaved over time in order to guarantee a degree of safety is maintained in the primary driving task (i.e., so that lateral deviation does not become too egregious), but also that the secondary iPod task is completed in a reasonably timely manner (i.e., so as to reduce the additional time costs that are incurred for too frequently interleaving tasks). Following Brumby et al.'s (2007a) analysis of dialing while driving, we evaluate the relative speed and safety of each of the possible task interleaving strategies. For simplicity in modeling the iPod task, we assume that each scroll movement is completed in chunks, such that attention can only be returned to driving in between steps in the task procedure (see Table 1 for details). This means that for the simple (podcast and video) selection tasks there are at least $2^2 = 4$ possible task interleaving strategies and for the complex (song) selection task there are at least $2^3 = 8$ possible task interleaving strategies.

Furthermore, we also explore the consequences of dedicating more or less time to steering control before returning attention to the secondary task. It should be clear that the steering control model provides an intuitive argument for the value of giving up more time to steering in certain circumstances by conducting a series of multiple steering updates in succession. For instance, if the car is far from the lane center, then an initial steering update

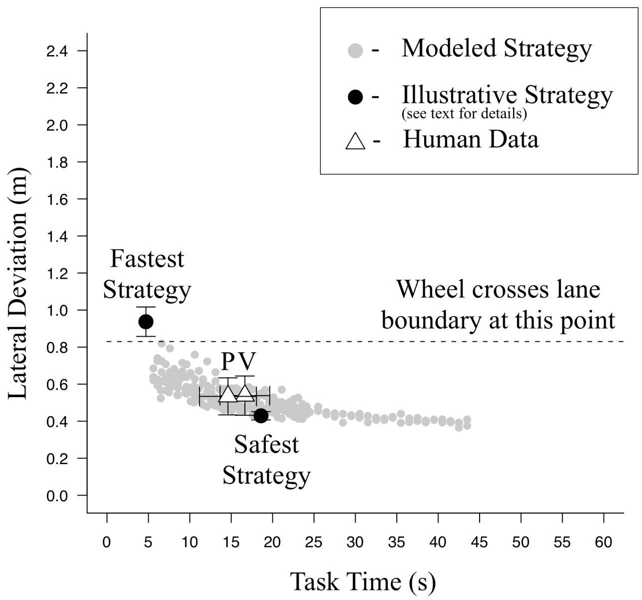

Figure 2: Data plot of task time and average lateral deviation predicted for each of the modeled strategies and human data for the simple (podcast and video) selection tasks. All error bars represent 95% confidence intervals of mean. Note: *P* = human data for the podcast selection task & *V* = human data for the video selection task.

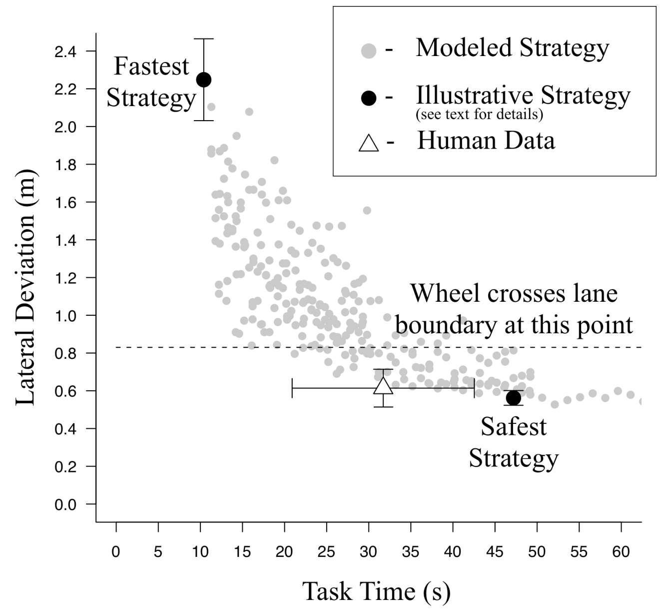

Figure 3: Data plot of task time and average lateral deviation predicted for each of the modeled strategies and human data for the complex (song) selection task. All error bars represent 95% confidence intervals of mean.

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. However, left unchecked the vehicle will continue along this sharp heading, possibly past the lane center and beyond. Further steering updates are therefore required in order to gradually stabilize the heading of the vehicle as it nears the lane center.

Thus, for each steering episode in a given strategy we varied the number of steering updates that were conducted before attention was returned to the secondary task from between one (i.e., making the total steering episode 0.5 s) and 30 steering updates (i.e., making the total steering episode 15 s). This upper limit was chosen because we found that conducting any more steering updates in sequence gave asymptotic performance across all of the iPod selection tasks. Each strategy was run for 50 trials and performance averaged.

RESULTS

Figure 2 shows the task time and average lateral deviation predicted for each of the modeled strategies and human data for the simple (podcast and video) selection tasks. Figure 3 shows the same data for the complex (song) selection task. The speed/accuracy trade-off that exists between completing the secondary task quickly and driving safely is apparent in each figure: The upper-left portion of each plot represents faster but less safe performance, whereas the bottom-right portion represents slower but safer performance. It is clear from both of the figures that the human data fall within the speed/accuracy trade-off space predicted by the model. We next focus on identifying the *fastest* and the *safest* strategies for completing each of the tasks.

The *fastest strategy* for completing each of the tasks is simple defined as the strategy that completes each of the secondary tasks in a single contiguous block without once returning attention to the primary task of driving. The predicted task time for fastest strategy is given by the sum of the task procedures; that is, 10.4 s for the complex song selection task, and 4.7 s for both of the more simple (podcast and video) selection tasks. It is clear from the figures that while adopting this strategy would complete the secondary task in the least amount of time, not taking the additional time to make a quick glance back to the road and adjust the heading of the vehicle would likely have catastrophic consequences for the primary driving task. Moreover, comparing performance between the simple and complex tasks (Fig 3 vs. Fig 4) suggests that lateral deviation predictions for this fastest strategy are highly dependent on the total time of the secondary task; lateral deviation increases with longer, more demanding secondary tasks.

Defining the *safest strategy* for completing each of the secondary tasks is more problematic because while giving up more time to steering control generally reduces the lateral deviation of the vehicle, this improvement gradually asymptotes. Brumby et al. (2007a) define the safest strategy as at the point where lateral deviation reaches asymptotic dual-task performance. In particular, we identify a subset of the strategies in the strategy space that do not significantly differ in terms of lateral deviation from the strategy that gives up the most amount of time to driving; that is the *slowest strategy* considered (see the right most data point in Figure 2), which we might intuitively presume to be the absolute safest strategy. A series of *t*-tests were conducted to reject strategies that gave lateral deviation predictions that were significantly greater than the lateral deviation of this slowest strategy. From this subset of strategies, which are basically statistically equivalent in terms of lateral deviation, the *safest strategy* is the strategy that also completes the secondary task in the least amount of time (shown in Figures 2 and 3).

Comparing the model predictions to the human data, it is clear that the human data fall within the bounds of the strategy space predicted by the model. Furthermore, it is interesting to note that the human data for all of the selection tasks lay closure to the model predictions of the *safest strategy* than the *fastest strategy*. Clearly this is not unexpected given the likely risks of adopting the fastest strategy.

However, the analysis also suggests that in order for a reasonable degree of driver safety to be achieved, particularly for more complex and time consuming secondary tasks, people can adjust their strategy by giving substantially more time up to driving. In particular, if we compare the difference in task time between the fastest strategy and the safest strategy for both the simple and complex selection tasks, then we find that for longer and more complex tasks safety can be achieved, but that it requires significantly more time to be given up to steering control in order to complete the task in a safe manner. Moreover, the analysis offers a potential explanation for why people behave the way that they do in terms of the trade-off between task time and safety.

GENERAL DISCUSSION

In this paper we have described a modeling technique for predicting the effects of using an Apple iPod portable music player while driving. In order to model the iPod selection task, an experiment was conducted to determine the time required to select a target from an order list using the scroll wheel on the iPod. It was found that a simple linear model accurately predicted the time to scroll through the list and select a target. This model was then used in conjunction with a previously reported steering control model (Brumby et al., 2007b) to derive *a priori* predictions for dual-task performance over the entire range of possible strategies for interleaving the two tasks. From this set of possible strategies, we focused on identifying the *fastest* and the *safest* strategies for completing both simple and a more complex selection task. It was found that the model predictions bracketed the observed human data from a recent study that investigated the effects of using an iPod while driving.

There are at least two possible concerns with the analysis described here. First, in modeling the iPod selection task, we assumed that each scroll movement was completed in chunks, such that attention could only be returned to driving in between steps in the task procedure. The reason for adopting this assumption was for simplifying the space of strategies that were evaluated. There is a clear concern that this assumption may be unrealistic though. In particular, for longer scrolling movements participants may have tended to pause halfway through the movement in order to check on the position and heading of the vehicle. A more elaborate evaluation of the strategy space could be conducted; however, a more fruitful approach might be to focus on gathering empirical data in order to determine the upper bound on the amount of time that people are prepared to spend on a secondary task in a single episode before returning to check on the primary driving task.

Second, the linear scroll model for predicting task time on the Apple iPod was based on an artificially simple search task, where participants located a known target in an ordered list. It is not clear to what extent this data applies to more complex searches with complex real-world content. We might speculate that the gradient of the scrolling function might be shallower for more complex searches. Nonetheless the extent to which the human data from Salvucci et al's (2007) study fit within the *a priori* performance predictions given by the model is a non-trivial feat.

Given people continue at an increasingly alarming rate to perform distracting tasks while driving, a clear implication of the work presented here is that efforts might be directed towards understanding how to better design mobile devices to make their use by the driver of a car less dangerous. The results of the modeling analysis presented here suggest that the total time that the driver of a car 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 a secondary in-car task. That is, designing mobile devices that facilitate short bursts of interaction as opposed to requiring long stretches of interaction might help to alleviate the effects of distracted driving.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grant #IIS-0426674. We would like to thank Mark Zuber for implementing the experimental software used in the Apple iPod selection study.

REFERENCES

Brumby, D.P., Howes, A., & Salvucci, D.D. (2007a). A cognitive constraint model of dual-task trade-offs in a highly dynamic driving task. In the *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 233-242). New York, NY: ACM Press.

Brumby, D.P., Salvucci, D.D., & Howes, A. (2007b). A bounded rational analysis of concurrent multitask performance while driving. To appear in the *Proceedings of the 8th International Conference on Cognitive Modeling*. Hove, UK: Psychology Press.

Brumby, D.P., Salvucci, D.D., & Howes, A. (submitted). An empirical investigation into dual-task trade-offs while driving and dialing. Paper submitted to the *British HCI Group Annual Conference*. Lancaster University, UK.

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* (pp. 403–413). New York, NY: Oxford University Press.

Kieras, D.E., & Meyer, D.E. (2000). The role of cognitive task analysis in the application of predictive models of human performance. In J.M.C. Schraagen, S.F. Chipman & V.L. Shalin (Eds.), *Cognitive Task Analysis* (pp. 237-260). Mahwah, NJ: Lawrence Erlbaum Associates.

Salvucci, D.D., Markley, D., Zuber, M., & Brumby, D.P. (2007). iPod distraction: Effects of portable music-player use on driver performance. In the *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 243-250). New York, NY: ACM Press.

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

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

Tsimhoni, O. & Liu, Y. (2003). Modeling steering using the queueing network – model human processor (QN-MHP). In the *Proceedings of the Annual Conference of the Human Factors and Ergonomics Society* (pp. 1875-1879). Santa Monica, CA: Human Factors and Ergonomics Society.