

## The Effects of In-Vehicle Distraction on Driver Response During a Crucial Driving Maneuver

P. A. Hancock

*University of Minnesota*

L. Simmons, L. Hashemi, H. Howarth, and T. Ranney

*Liberty Mutual Research Center for Safety and Health, Hopkinton, MA*

In this article, we report the effects of the presence of an in-vehicle distracter (a telephone, number-matching task) on driver reaction to a light-controlled stop. Ten volunteer drivers were asked to perform 60 repeated circuits of a closed-loop test track, in which each circuit represented an experimental trial. At the beginning of each trial, the driver was presented with a unique 7-digit memory set. In addition to the memory requirement, the first digit of the memory set was used during driving in the distracter task. On 30 circuits, which was 50% of the total trials, neither the distracter nor the traffic control device was activated. On 10 circuits, only the distracter task was presented, which required the driver to compare a presented number with the first digit of the memory set and to indicate either a match or a mismatch via touch-screen activation. On another 10 circuits, a standard traffic signal changed from green to red, requiring an immediate stop. On 10 circuits, both the distracter and the traffic control device were activated together. Drivers were asked to recall the entire 7-digit string at the end of every trial. The whole sequence was repeated at a slow, approximately 20 mph, and a faster, approximately 30 mph, speed. The order of circuits within each speed condition was randomized so that drivers were unable to predict the occurrence of either the distracter or the light activation. Results indicate slower brake response times to the change in the traffic control device (onset of a red light) in the presence of the in-vehicle distracter. However, drivers exhibited significantly shorter stopping times to this red light activation in the presence of the distracter. Despite this latter effect, the margin of safety, as represented by stationary distance from the intersection, was significantly reduced approximately 25% in the presence of the distracter. In addition, there were variations in the distracter response accuracy and the digit-recall memory that affirmed the deleterious effect of a competing task at this crucial driver decision point. These results are discussed in terms of erosion of a safety margin in the presence of in-vehicle sources of distraction that are expected to increase significantly in the face of unregulated proliferation of Intelligent Transportation Systems in-vehicle devices.

Since automobiles first made their appearance, there have been passengers and devices in the vehicle that can potentially act to distract the driver from the primary task of vehicle control. The introduction of the car radio signaled a clear recognition that because much of driving is performed automatically, without significant conscious attention (cf. Groeger, 1999; Ranney, 1994),

individuals are easily able to cope with additional information, especially if it does not contend for visual attentional resources (Wickens, 1987). However, it is also clear that the context of distraction is crucial. What may be merely an annoyance or redirection of attention in unstressful moments may prove the trigger for a fatal crash in highly stressful driving environments. So, although vision itself has been an area of traditional concern for the driver behavior community (e.g., Gale, Freeman, Haslegrave, Smith, & Taylor, 1986; Rothengatter & Carbonell Vaya, 1997), there are many contemporary efforts to investigate driver attentional strategy as a crucial area of understanding (e.g., Ranney, 1994).

Such issues have been thrust to the forefront of concern with the advent of Intelligent Transportation Systems (ITS). In response to increasing capacity demands, elevated congestion, and ever-improving vehicle capabilities, ITS has sought technologies to answer these pressing concerns, and in respect of their implementation, the necessity to understand driver attention has become an urgent issue (Hancock & Parasuraman, 1992). From one or two potential sources of distraction, we now face the prospect of perhaps hundreds<sup>1</sup> of in-vehicle displays and information sources. How we ensure that the primary task of vehicle control is never compromised under these circumstances is perhaps the vital safety issue of ITS development and deployment as safety and efficiency threaten to come into conflict. At present, the inclusion of additional in-vehicle devices is largely unregulated. Adding multiple display screens can obviously represent a significant source of attentional distraction that can overwhelm the driver with a degree of workload that cannot be reconciled with safe driving performance. However, how many such sources might still be safe and what their specific characteristics might be has yet to be determined.

One contemporary device, which might be regarded as the forerunner of many in-vehicle technologies is the mobile phone. Mobile phones were first introduced commercially in the United States in 1983 and were installed in vehicles shortly thereafter. Although it is possible to eliminate the potential for distraction by turning phones off while in motion, such action can defeat the very purpose of these devices, especially if such phones are fixed within the vehicle itself. Concerns about the distraction caused by mobile phones have led to a number of studies that have recently been reported by the National Highway Traffic Safety Administration (see Goodman et al., 1997; for a summary, see Goodman, Tijerina, Bents, & Wierwille, 1999). Their conclusions were that for simulator and test-track studies, when compared to driving alone, manually dialing a cellular phone can have a deleterious effect on vehicle control, including such activities as lane keeping and speed maintenance (see also Alm & Nilsson, 1994; Serafin, Wen, Paelke, & Green, 1993; Stein, Parseghian, & Allen, 1987; Zwahlen, Adams, & Schwartz, 1988). In a closed driving course environment, however, this effect was not always found (see Kames, 1978). In addition, for on-road studies in which there was a manual dialing task, it was demonstrated that both dialing and radio tuning can have a negative impact on driver eye glances away from the road scene and on driving performance (Tijerina, Kiger, Rockwell, & Tornow, 1995). However, conflicting results were reported for the amount of visual sampling required for manual dialing tasks versus radio tuning (cf., Hayes, Kurokawa, & Wierwille, 1989; Tijerina et al., 1995).

Several studies concerning the concurrent demands of driving and secondary tasks, which represent telephone communication, have been conducted using interactive driving simulators (e.g., McKnight & McKnight, 1993; Serafin et al., 1993; Stein et al., 1987). One obvious reason for this is that simulation is a benign environment where danger can be largely eliminated. Yet simulation has been criticized for just such a suspension of reality, and thus other studies have expressly focused on actual on-road conditions (e.g., Hayes et al., 1989; Tijerina et al., 1995).



Obviously, on-road studies have the highest face validity and yet great care must be exercised so that both experimental and incidental drivers are not intentionally exposed to elevated sources of hazard. Unfortunately, it may well be these dangerous or demanding situations that represent the very crux of the safety problem. In this respect, test-track evaluation can provide an important compromise, exposing drivers to actual vehicles and roadways but in sufficiently controlled circumstances such that unaware drivers and innocent bystanders are not put at risk. Test-track evaluation was thus chosen for this experimentation.

Given our present use of test-track facilities, it is important to examine the results of previous experiments that have pursued similar experimentation in such conditions. We have found three such studies. The earliest was conducted by Brown, Tickner, and Simmonds (1969) using an airfield location. Messages conveyed to drivers were transmitted over the phone and were structured in the form of a Baddeley (1968) reasoning test. This task required the driver to respond either *true* or *false* to a conclusion, depending on the information in two preceding propositions. The reasoning task was performed in a nondriving, control condition and while driving on the airfield, Brown and his colleagues found that both response time and response accuracy for the reasoning task were impaired during driving. They concluded that "some mutual interference between the concurrent tasks is inevitable under conditions of telephoning while driving on the road" (Brown et al., 1969, p. 423). The general conclusion from these results is that the degree of decrement in driving that can be expected is contingent on the nature of the subsidiary task demands and to an extent on the skill level of the individual driver (see also Hancock, 1986).

A subsequent test-track evaluation of telephoning while driving was reported by Kames (1978). The prime concern was for the efficacy of different forms of in-vehicle telephone designs. The fundamental finding was that, if located within the reach and sight of the driver, the design per se had little influence on driving performance. Kames also recorded reaction time as a subsidiary measure, but in the short report these results were, unfortunately, not included. There were some minor decrements, but as has been noted, it is not clear whether such small variations could represent a safety hazard. The final study using a test-track environment was that of Zwahlen et al. (1988). They conducted two experiments using 10 participants each, again on an unused airport runway. These authors were also interested in different forms of telephone design, but for the present purpose the most salient information recorded was the measure of lane deviation while phoning. The authors found that maximal lane deviation occurred during the actual dialing event and that phone position was also an important issue.

The consensus of these three studies is that driving performance can be impaired through the use of such in-vehicle systems, which themselves represent a specific form of real-world secondary task. However, with the possible exception of the gap assessment task in the study by Brown et al. (1969), performance requirements did not occur during critical phases of driving but rather during very benign conditions. It should be noted here that the three extant studies using test-track facilities are now rather dated. The study by Brown and his colleagues is now some 3 decades old, and even the study by Zwahlen et al. (1988) was conducted before the major ITS initiatives focused such a great degree of effort on the area of in-vehicle technologies. Since those experiments there have been major changes, not simply in the vehicles under examination but especially in the size and capability of technologies such as cellular phones that mean that reevaluation employing contemporary systems is vital. Indeed, it is for this specific reason that our display used a generic, contemporary phone representation presented on a touch screen in order to retain a level of generality applicable to the spectrum of anticipated technical innovations.

Finally, with respect to in-vehicle phone use, there is the question of existence proof. Because there are already many thousands of phones in vehicles and records are now beginning to be kept concerning their involvement in crashes, it is becoming possible to examine the frequency of such crashes and establish an estimate of safety impact through epidemiological approaches (see Redelmeier & Tibshirani, 1997). Although such a possibility has been addressed elsewhere (see Hancock & Scallen, 1999; Violanti & Marshall, 1996), the contention here is that driving, a partially automated, over learned task, can frequently be performed to a satisfactory level with a minimal investment of attention. Thus the context of evaluation is crucial. There are many circumstances in which the driver can rely on expectation and even periodic open-loop control and still retain safe passage. However, occasionally conditions arise in which full attention must be devoted to driving. Such events can be categorized along a continuum ranging from the totally predictable to the totally unpredictable. Those events toward the unpredictable end include acts such as another driver suddenly serving into one's driving lane, or a child running out from behind a parked vehicle. But these are rare and somewhat unusual. In normal driving, significant, attention-demanding events arise that are almost completely predictable. These include circumstances such as heavy freeway traffic or decisions at road intersections (Hancock, Wulf, Thom, & Fassnacht, 1990). In these traffic situations, the driver has to cope with sudden increases in demand and it is at these times that drivers are, on a regular basis, most vulnerable to the deleterious effects of distraction. In this article, we do not deal with driver response to unexpected demands, but rather we focus on driver response to conditions in which high workload may be anticipated.

Therefore, in respect of the need for further and contemporary test-track evaluation and particularly because we believe that the contextual aspect of distraction is crucial to an assessment of in-vehicle technology safety, this research examined the effect of the presence of a distracter on driver response at a changing traffic signal light. The distracter was configured as a mobile phone activation, because mobile phones themselves are, in reality, the earliest and currently the most prevalent form of ITS implementation.

## EXPERIMENTAL METHOD

### Experimental Participants

Ten licensed Massachusetts drivers were recruited as volunteers for the study. There were 5 male and 5 female drivers whose age ranged from 26 to 46 years, with a mean of 36.0 years.

### Experimental Apparatus

The driving tasks were implemented on a test track (see Figure 1). This consisted of a closed-loop  $\frac{1}{2}$  mile of two-lane road delineated to allow continuous driving, a simulated intersection equipped with standard traffic signals, and a control booth from which the experimenter monitored data collection and drivers' responses. Four pairs of inductive loops, buried beneath the pavement along the approach to the intersection, were used to monitor vehicle position. All participants completed the experiment in an instrumented 1991 Ford Crown Victoria with automatic transmission. The vehicle was equipped with a DATRON DLS-2 optical sensor used to collect continuous speed information, a brake activation sensor, and a 10 in. flat-panel LCD touch screen (CyberResearch, Inc.), used to display the image of a simulated cellular phone. A laptop



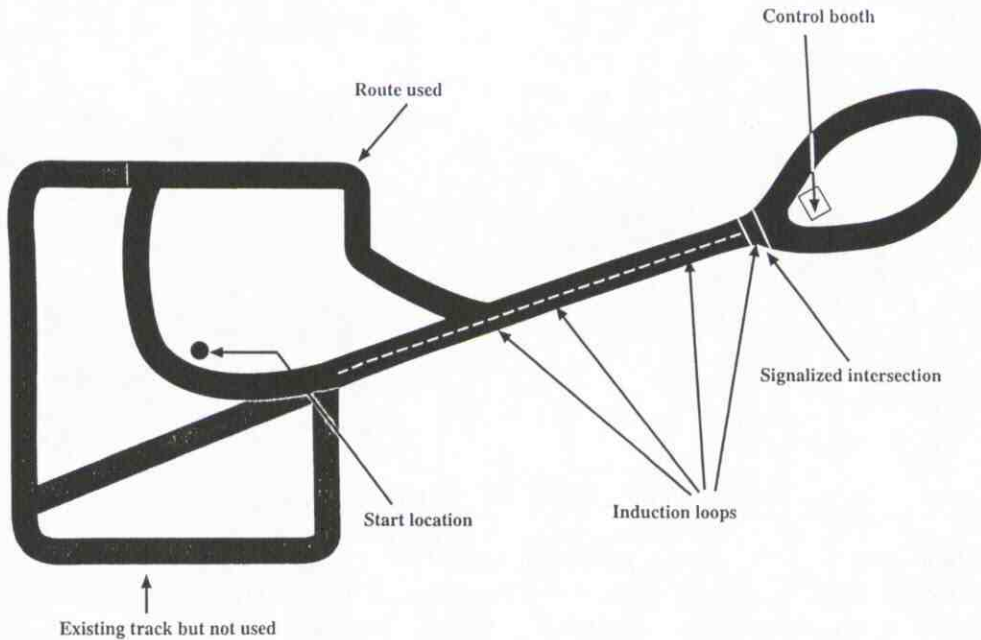


FIGURE 1 Diagram of the test-track facility.

PC, located in the rear seat of the vehicle, was used to transmit data to the control booth PC using a high-performance, wireless industrial modem. The vehicle was also equipped with a two-way radio to allow communication with the experimenter in the control booth, which was only used between trials to communicate any queries the driver might have. Computers located in the booth controlled data acquisition, timing of traffic signal onset, and presentation of stimuli on the simulated cellular phone.

### Experimental Design

During the experiment, participants drove the instrumented vehicle around the track. For each lap, participants began at a starting location (see Figure 1) and drove toward, and through, the signalized intersection before returning to the original starting location. The experiment consisted of four main tasks:

1. *Number memorization and recall task:* At the beginning of each lap, a seven-digit phone number was presented on the display screen of the simulated cellular phone (see Figure 2). Participants were asked to memorize the phone number, then press a button on the simulated phone key pad to indicate they were ready to begin driving toward the intersection. At the end of each lap, participants were asked to recall the phone number and enter it into the simulated cellular phone using the keypad on the touch screen. They were given no immediate feedback concerning their performance on this task, although they were given a summary of their earned reward-penalty at the end of each block of driving, as is detailed later. We recorded the recall



FIGURE 2 Representation of the in-vehicle phone interface.

accuracy of the memorization task for subsequent analysis. The purpose of the digit-recall task was twofold. First, memorization of seven-digit number is not an uncommon task in actual phone usage and perhaps not uncoincidentally, the memory of seven digits is close to the limit of working memory as communicated in Miller's (1956) classic article. Second, the digit-recall task served as a secondary loading task that has been demonstrated previously to interact with roadway geometry and traffic density in a simulated driving task (Kantowitz, 1995). Because the present experiments were conducted on a closed-loop test track on which other vehicles were not allowed, we sought to provide additional cognitive loading and the memorization task served this function.

2. *Speed maintenance*: At the beginning of each major experimental block, drivers were informed of the requested vehicle speed. These were, respectively, 20 and 30 mph. The task of the driver was to maintain that speed on the approach to the intersection. A record was kept of individual trial speeds. However, as most drivers were successful in maintaining the required speeds and did not deviate significantly from the requested speeds, we consider that this manipulation was successful and report the respective differences at the two achieved vehicle velocities.

3. *Distracter task*: On one third of the 60 trials, as the vehicle approached the intersection, a tone sounded and a single digit appeared on the phone display screen. Participants pressed a key on the phone pad to indicate whether the digit was the same (a match) or different (a mismatch) from the first digit of the memory string presented at the start of the lap. Again, although performance on this task was included in the reward-penalty structure, drivers were given no immediate feedback as to their individual trials' performance level. For the purpose of subsequent analysis, we recorded response accuracy.

4. *Stopping task*: On one-third trials, as the vehicle approached the intersection, the traffic signal turned from green to red, requiring participants to stop the vehicle as quickly as possible before reaching the stop line in front of the intersection. Our purpose in eliminating the intermediate yellow light was to examine the influence of a distracter on a clear and unequivocal driving decision. As a result, we did not wish to introduce the uncertainty that yellow-light activation introduces (see Senders, 1998). Further, this form of go-no go decision more easily gen-

eralized to several other critical driving decisions. The traffic signal was activated, based on the driver's approach speed, to provide a specified amount of time before the intersection. Distance from the stopping line was used as the dependent variable for this task.

The experiment consisted of four conditions. The first was a control situation in which no stopping task or distracter task was presented. The second condition required response to the distracter task only, whereas the third required participants to stop in response to the traffic signal changing from green to red. The final condition combined both the distracter and the stopping task together. There were 10 trials in each condition, except for the control condition, for which there were 30. This allowed the stopping task to be presented in only one third of all trials, so that the traffic signal change would be relatively unexpected. For the same reason, the distracter task was presented on only one half of the stopping trials. The order of conditions was randomized within one speed, and the speeds were presented as blocks that were counterbalanced across drivers. Each participant completed 30 trials at each of two approach speeds (20 mph and 30 mph), for the total of 60 trials.

In order to encourage drivers to accomplish the imposed tasks, a reward-penalty system was enacted. A small monetary reward (10 cents) was given for each correct response and a penalty of equal value was given for each incorrect or missed response for both the number-matching and the digit-recall tasks. A penalty was given if the driver activated the brake inappropriately on trials that did not include a red light, and these false alarms cost 50 cents. Correct responses to the red light were rewarded with \$1, and the same amount was deducted if a driver missed a red light. Although drivers were not given immediate feedback on their task performance, they were shown a summary of their accumulated rewards-penalties after each block of 20 trials. If drivers accumulated a negative amount by the end of a block, no monetary reward was given for that block.

### Experimental Procedure

At the beginning of the experiment, participants were given instructions concerning the vehicle controls and navigation around the closed-course track as well as demonstrations of all the tasks in the experiment. Following training on each task, each participant completed four practice laps (one for each condition) at each of the two approach speeds (20 mph and 30 mph), for a total of eight practice laps. The experimenter remained in the passenger seat during all training and practice. Following completion of the practice, participants began the experimental trials. For these trials, participants were alone in the vehicle but were able to maintain contact with the experimenter through the use of a two-way radio located in the vehicle that was used only between trials.

### Analytical Design

The model used in this study employed a mixed analysis in which the sex of the participant was a between-subject variable, and vehicle velocity and the activation of the in-vehicle distracter were within-subject variables. As indicated earlier, the repetitions on the distracter, the stopping task, and combined condition were equal, whereas the no light, no distracter control had three times as many trials. There were several dependent variables derived from drivers' responses, some of which could only be recorded in the red light activation condition. These included aspects of vehicle control, which were designated as the primary task performance, and aspects



of distracter task performance, which was of secondary importance. With respect to vehicle control, we recorded *brake response time* (BRT), which was defined as the time in seconds from the change of the traffic light to the onset of brake response; the *stopping time* (ST), which was the time in seconds from the activation of the brake to a full stop of the vehicle; and intersection *stopping distance* (SD), which was the distance in feet that the vehicle stopped before the line indicating the front boundary of the intersection. In general, shorter BRT's, shorter ST's, and longer SD's were considered representative of good performance, although, as will be discussed, there are circumstances in which this may not necessarily be the case. With respect to the secondary task, we recorded the accuracy of the distracter response and the accuracy of seven-digit recall task in which again, greater accuracy was considered better performance. Such statements concerning performance might, at first, seem self-evident. However, part of our subsequent discussion concerns the reliance on these optimized forms of performance as representative of more global concepts such as driver safety.

## EXPERIMENTAL RESULTS

Analyses of variance (ANOVAs) were computed individually for each of the performance measures using the General Linear Model procedure in SAS/STAT® Software, Version 6.0 (SAS Institute, 1990). In order to satisfy the assumption of normality (using the Shapiro-Wilk test; Shapiro & Wilk, 1965), logarithmic transformations were applied to the BRT and ST measurements. We first considered the effects of sex.

### Sex Differences

Although the average BRT was slightly higher for women (0.95 sec) compared to men (0.90 sec), this difference was not significant ( $p = 0.7282$ ). Men exhibited slightly greater variability in BRT (0.29 sec), compared to women (0.25 sec), but again this difference failed to reach traditional levels of significance. The average ST was also greater for women (1.96 sec) than for men (1.3 sec;  $p = 0.0799$ ). However, the variability of ST was similar for both groups (1.30 sec). From these results we can confirm that we found no substantive sex differences in the present limited sample. As a result of this finding, we have collapsed across sex in the analyses that follow.

### BRT

Figure 3 shows the effects of the presence of the distracter (in the left panel) and vehicle speed (in the right panel) on recorded BRT. The average BRT increased from 0.61 sec to 0.93 sec in the presence of the distracter, which was confirmed as significant in the ANOVA,  $F(1, 9) = 115.1$ ,  $p < .0001$ . The average BRT at the high speed was faster (0.68 sec) than at the low speed (0.78 sec), which was also confirmed as significant in the ANOVA,  $F(1, 9) = 6.23$ ,  $p < .05$ , although in real terms the driver traveled approximately 30 ft during the former response latency compared to 23 ft during the brake response latency for the slower speed. Thus, under the identified conditions, the presence of the distraction resulted in drivers responding more slowly and with greater variability when the source of in-vehicle distraction was present. Also, drivers responded more quickly (and with less variability) when they were driving at a faster speed, which is discussed later as a form of response adaptation. The interaction between speed and distraction was not significant.



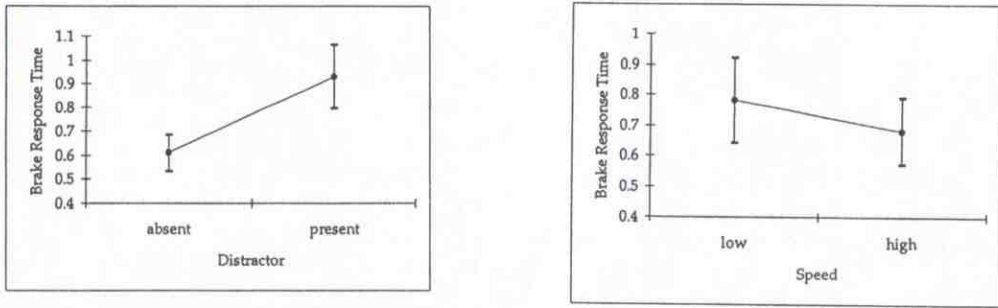


FIGURE 3 The effect of the presence of an in-vehicle distracter (left panel) and vehicle speed (right panel) on brake response time.

## ST

As with BRT, there was a significant difference in ST due to vehicle velocity,  $F(1, 9) = 25.29$ ,  $p < .0001$ . For the presence of the distracter, the effect on stopping time approached traditional levels of significance,  $F(1, 9) = 3.41$ ,  $p = .06$ . Again, as with BRT, the interaction between velocity and distraction was not significant. Figure 4 shows the main effects of the presence of distracter and speed, respectively. Drivers stopped more quickly ( $M = 1.66$  sec,  $SD = 1.32$  sec) in the presence of the distracter than they did when it was not present ( $M = 2.55$  sec,  $SD = 2.55$ ). Drivers also stopped faster (2.07 sec) when they were driving at a higher speed than when they were driving at a lower speed (2.14 sec).

## SD

A further reflection of the tendency to respond more slowly and with greater variability in the presence of the distracter was evident in the results that recorded how far from of the intersection line the driver stopped. An SD of zero means stopping exactly on the line, and greater values for SD mean greater distances from the intersection. There was a significant influence of distracter presence on SD,  $F(1, 9) = 61.84$ ,  $p < .0001$ . Further, there was a significant effect for speed on SD,  $F(1, 9) = 10.39$ ,  $p < .01$ . There was no significant interaction between these factors. With no distracter, drivers stopped an average of 35.3 ft in front of the line, whereas in the presence of the distracter, drivers stopped an average of 9 ft closer at 26.3 ft (see Figure 5). This represents a 24% decrease in the stopping safety margin. Drivers stopped an average of 29.2 ft in front of the line while they were driving at a low speed and an average of 32.7 ft in front of the line while they were driving at a high speed (see Figure 5).

## Distracter Task Response Accuracy

The previous measures all represent reflections of performance on the primary task of vehicle control. However, there is the question of distracter response itself. Overall, distracter response accuracy was very high. The mean overall response accuracy was 97.9%. There was a tendency for drivers to respond slightly more accurately to the distracter (98.9%) when they were not required to stop at the intersection, compared to their performance during the stopping condition (95.9%). This difference was altered with the change in speed. At the low speed, the distracter

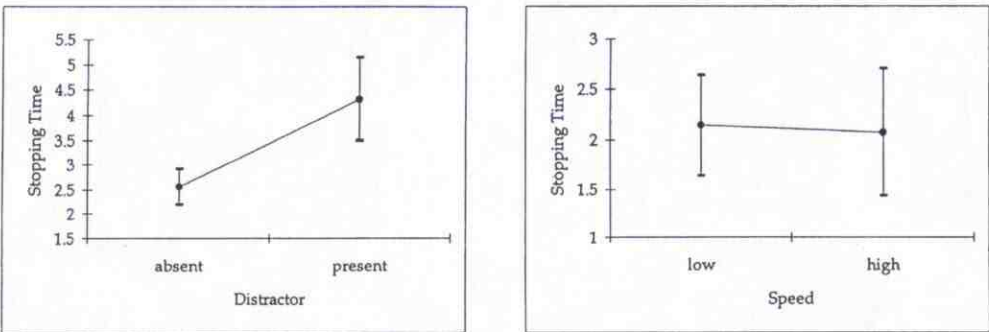


FIGURE 4 The effect of an in-vehicle distracter (left panel) and vehicle speed (right panel) on stopping time.

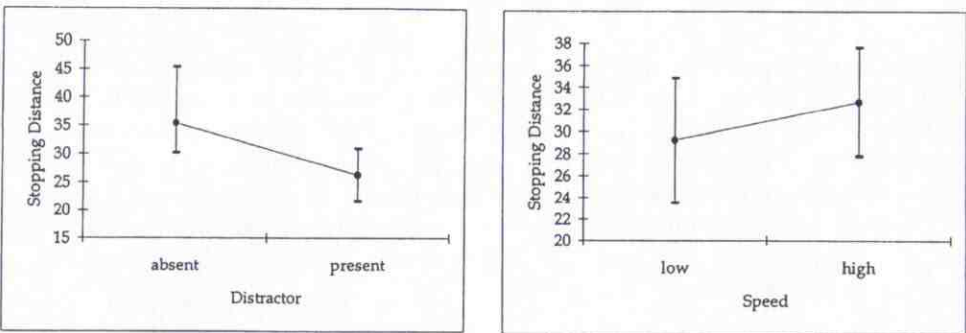


FIGURE 5 The effect of an in-vehicle distracter (left panel) and vehicle speed (right panel) on stopping distance.

recall was basically unaffected by the presence (98.8%) or absence (97.8%) of the red light. However, at the high speed, trials without a stop were performed without error (100%). In contrast, trials with a required stop at the higher speed showed a substantively lower recall accuracy (92.9%). In considering these findings, it should be remembered that even in the high speed, stopping condition, accuracy was still very near to the ceiling of possible performance.

### Number Memorization Recall Accuracy

When drivers were asked to recall the seven-digit number at the end of each lap, they responded correctly 89.3% of the time. However, they were more accurate at low speeds, with 92.4% accuracy, than at high speeds, with 85.7% accuracy. Again, this is supporting evidence that the loading task was effective and that the main results are not due to load shedding on behalf of the drivers.

### DISCUSSION

The results of this experiment are, at first blush, both simple and intuitive. The presence of the distracter competed for attentional resources such that the change in light was recognized later than in the light-only condition. The evidence in support of this comes in the form of a signifi-



cant increase in BRT. However, having recognized the light change in the presence of the distracter, the driver braked more intensely in an attempt to compensate for this later detection. This pattern of behavior is evident in the shorter STs. Taken together, these patterns suggest that drivers engage in greater braking severity in the distraction condition, and this pattern of response may represent a hazard for close-following vehicles. However, despite this adaptive response in which action provided some compensation for increased perceptual latency, the driver is still, on average, not able to make up for all of the lost time in the detection phase and ends up closer to the intersection, thus ending with a reduced margin of safety. These results therefore suggest that in the presence of the distraction, drivers are responding closer to the boundary of performance represented by their own reactions and the physical braking characteristics of the vehicle. From the evidence, it appears that the memorization task does provide a degree of cognitive loading. Given that the poorest recall is also evident in the most taxing driving situation, it does not appear that these results can be attributed to load sharing, in which the driver trades performance level on the primary task for performance on the secondary task, and thus the results are a true reflection of imposed demands.

Thus far, the evidence supports a coherent story of competing task demand. Further, given the location of the light-control device and the distracter screen in the driver's field of view, it appears more likely that the competition is one for attentional resources, rather than a need for a greater number of discrete eye fixations—although eye-fixation evidence is critical for evaluation of in-vehicle technologies (see Gale, 1997). If we were able to conclude here with just these simple patterns, the experimental picture appears consistent. Because the results are highly consistent with previous findings and are also in the direction of clear intuition and psychological theory such that one should react more slowly in the presence of distraction, it appears, initially, that they represent yet another warning concerning the potential for driver overload from additional sources of stimulation (see Hancock & Parasuraman, 1992). However, there are several issues that are of crucial importance that relate not only to the present results but other similar efforts at establishing safety limits for burgeoning in-vehicle systems.

The first question to be faced is to what degree these results are informative concerning the assessment of the safety of in-vehicle devices. One of the great problems of behavioral research is the question of instruction. In this experiment, the drivers were given training on the specific tasks and then told to drive in accordance with their best (and safest) performance. Further, a reward structure was developed to reinforce this instruction set. In these experiments, our purpose was to elicit optimal performance such that changes due to the independent variables of traffic control device and in-vehicle distractor would be maximized, and indeed this is the standard tactic in behavioral experimentation. But is this how drivers drive? In accord with a model of stress and performance presented earlier by Hancock and Warm (1989), we suggest that during normal driving, that is, unstressed conditions, individuals have a variety of performance strategies open to them because the objective of performing the task to a satisfactory level can be achieved in any number of ways. However, as greater levels of stress are imposed on the individual, being directly analogous with increased momentary demands in driving, the number of successful strategies available are reduced. This reduction is reflected as an increase in the spatial and temporal constraints on successful behavior. At the highest possible levels of stress, a single response strategy denotes success, and in a comparable manner in driving, emergency collision avoidance may be represented by one single course of action.

By placing individuals under an elevated degree of momentary demand in this experiment, we have shown how the safety margin, which is equivalent to the range of successful performance strategies (or more generally the range of adaptation), is reduced. The question still remains

whether this level of distraction is "safe." To answer this question, we have to define what we mean by an *acceptable level of safety*. In the original model conception of Hancock and Warm (1989), there were three fundamental states of performance. The first is a stable state and is represented in driving by normal, nonchallenging conditions. The second is a transient state in which the demands of the environment are sufficient to tax the adaptive capability to its limits. In behavior, we see symptoms of such states as attentional "narrowing" and task shedding, and through such strategies, primary task performance remains at a uniformly high level. In terms of driving, this may be seen in the sudden onset of bad weather in which the driver ceases conversation, turns off radios or compact discs, and focuses exclusively on the road. However, when we add additional demands to this transient state, we see the onset of a failure state in which performance level decreases rapidly, and the decline in capability takes the form of an exponential curve. In both physiological and behavioral functioning, such observations indicate the onset of catastrophic and potentially unrecoverable conditions. In driving, such failure may be evidenced by events such as loss of vehicle control. These observations help us to define the limits of a *safety envelope* that can now be defined as the transition point between stable and transient states of operation (see Hancock & Warm, 1989). Given this definition and given these results, we can now answer the question as to whether the in-vehicle distraction, represented by phone activation, caused unsafe behavior at this test-track intersection—the answer being that safety was not compromised to this necessary degree in this context. The final codicil is crucial to our discussion. We cannot neglect the obvious criticisms that are raised about test-track evaluation, that being there are no other competing road users present. However, although other road users may well represent additional demand to the driver, we have to recognize the social context of driving such that the other driver may well increase safety by, for example, warning an unwary driver, or taking avoiding action themselves in collision likely situations. Consequently, because other road users are adaptive entities in and of themselves, they may well act to dissolve hazard, as well as present hazard, as is their usual characterization (see also Gibson & Crooks, 1938).

There is little doubt that one of the crucial stimuli for new Intelligent Vehicle Initiative is safety. To promote safety, there is a concerted effort to develop in-vehicle warnings of impending collision (see Horowitz & Dingus, 1992; Knipling et al., 1993; Parasuraman, Hancock, & Olofinboba, 1997). These safety promoting technologies must sit alongside other in-vehicle devices, such as map navigation systems, which are themselves directed to the achievement of enhanced transportation efficiency. Can such multiple systems be inserted into the vehicle without compromising driver safety? We have suggested that driving is a combination of extended periods of satisficing behavior to minimal demands, interspersed with brief periods when increased performance effort is required. That is, for the large majority of driving, drivers perform well enough to accomplish their task but do not seek explicitly to optimize or improve their abilities, this being the definition of *satisficing behavior* (see also Hancock & Scallen, 1999). If this proposition is correct, then these results must be viewed as point measures on a general curve of declining capability. In this study, the distracter eroded the available safety margin, however, not to the extent that the drivers were unable to perform the task satisfactorily. This should not be unexpected because we tested young, fit, and experienced drivers who were practiced on the task and only asked to drive at moderate speeds at best. Consequently, it would be surprising if they had not been able to perform the task. The fundamental question revolves around the context of performance and the demands placed on the driver. We suggest that the level of demand was sufficient to induce driving impairment but not sufficient to induce a change from a stable to a transitional state. It is probable that as additional in-vehicle distractions are added, as driver competence decreases, perhaps through aging or inexperience, and as



momentary driving demand peaks through a concatenation of traffic conditions, the confluence of factors can push some instances of performance beyond acceptable limits. It is tempting, of course, to suggest that such circumstances are substantively and causally related to accidents. However, even this hope is simplistic, because as we have noted, for example, pedestrians and other vehicles are not inanimate objects but are controlled by individuals who can register poor and decreasing levels of performance in another person and make their own appropriate corrections accordingly. Thus, single vehicle, loss of control crashes may well be the primary and most pristine source of data in examining the effect of proliferating in-vehicle systems.

### PRACTICAL RECOMMENDATIONS

In this work, we have emphasized the crucial nature of the momentary context in influencing driver behavior and have indicated that there are periodic events that require full and undiverted attention to the task of vehicle control so that safe passage is maintained. However, we recognize that there are many more occasions in which the context does not demand such an all-immersing focus. Therefore, we have to try to implement "safety" as it relates to each of these conditions. As a result, from these results, we would suggest the following design guideline. In addition to our standard set of displays, there should be no more than two additional in-vehicle displays that can distract attention from vehicle control. This recommendation follows from our findings that one additional in-vehicle displays erodes the current safety margin toward the inflexion point of performance degradation discussed earlier. Such an assertion requires further empirical confirmation through evaluation in the context of crucial avoidance actions. It is important to note that this does not necessarily mean that there could only be two in-vehicle displays in total, because technologies such as heads-up displays and vision-enhancement displays are directly designed to facilitate vehicle control, and other information displays could be integrated with them. However, for those tasks that do not relate to the momentary control of the vehicle, we propose that two additional displays represent the maximum number, until it is established through direct in-vehicle testing that more displays do not further erode the margin of driver safety. Thus the burden of safety lies with those who would introduce such systems (see also Hancock & Scallen, 1999). The way in which such interfaces could be designed and integrated as forms of emergent display represent a significant challenge to future automotive design.

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### NOTE

- 1 Although it is doubtful whether there will ever be hundreds of other display screens in the vehicle, even a single video display terminal with hierarchic menu structures can provide potential access to this many displays. Similarly, and in a somewhat paradoxical manner, the proposal for ever increasing numbers of in-vehicle collision warning and avoid-

ance systems implies a further increase in display necessity. Of course, this could lead to tautological justification. That is, drivers must have artificial collision warning systems because their attention is always distracted from the road by collision-warning display activation!

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