In-vehicle workload assessment: Effects of traffic situations and cellular telephone use

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Received 18 October 2004; received in revised form 9 July 2005; accepted 21 October 2005
Available online 3 March 2006

Abstract

Problem: Assessment of drivers’ on-road workload is an important traffic safety consideration. This study was conducted to examine the effects of cellular phone communication on driving performance, with particular emphasis on variations in task demand in different traffic situations.

Method: Twelve participants were asked to drive on urban roads and motorways with or without concomitant mathematical-addition tests relayed via cellular phone. Measurements included task and driving performance, physiological responses, and compensatory behavior.

Results: Analysis of task performance revealed that mean response time was markedly increased (11.9%) for driving on urban roads compared to motorways. The mean driving speed only decreased 5.8% in the presence of phone tasks in comparison to normal driving without distractions. In addition, overall physiological workload increased through compensatory behavior in response to the phone tasks.

Conclusions: Driving with phone use in different traffic environments induced measurable variations in driver workload.

Impact on Industry: When faced with heavy traffic, a greater safety margin is typically adopted, with more lowered driving speed and restricted phone use, and it can be assumed that there is a general trade-off between tasks to preserve driving safety.

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Keywords: Driver workload; Cellular phone; Driving performance; Distraction; Heart rate

1. Introduction

Maintaining driver alertness and performance is an issue critical to ensuring transportation safety. However, both are dependent on operator workload and attentional resources. Where the performance demand exceeds the effective capacity of the drivers, there is a greater risk of accident. If workload is too low, however, then boredom or complacency may set in and critical monitoring functions may be degraded (Parasuraman, Molloy, & Singh, 1993). According to Verwey (1993), driver inattention plays a role in about 30–50% of all accidents. More recently, information overload has been exacerbated by the introduction of a variety of in-vehicle information and communication systems. In particular, ownership of cellular phones has increased dramatically in recent years. An analysis of the Taiwanese statistics reveals that cellular phone subscribers totaled 22.6 million in April 2002, giving a penetration rate of 100.7% and exceeding one account per person (Directorate General of Telecommunications, 2003). Furthermore, a great deal of attention has been focused on the potential distraction of mobile-phone use, and the inevitable impact on driving performance and potentially increased accident risk (Alm & Nilsson, 1995; Brookhuis, DeVries, & De Waard, 1991; Consiglio, Discoll, Witte, & Berg, 2003; McKnight & McKnight, 1993). Moreover, Redelmeier and Tibshirani (1997) also found that the use of cellular phones in automobiles was associated with a quadrupling of collision risk during the brief period of the call. Understandably, public concern for traffic safety has arisen over the demands on the driver from secondary information.
sources, and the implications of this in terms of safe vehicle operation. Thus, assessment of driver workload while performing driving-irrelevant tasks and managing attentional resources is a topic of critical importance in transportation safety.

Within the last three decades, the applied science community has demonstrated considerable interest in the concept of mental workload with respect to task demand and complexity, excess task capacity, and the ability to respond to unexpected events (Wickens & Hollands, 2000). Determination of workload imposed on a human operator plays an important role for designing and evaluating an existing situation. The term ‘workload’ is vague, however, and open to different interpretations, which tend to be based on the general concepts, task demand, effort expended, and the results of that effort (Roscoe, 1978). In the present study, workload was defined based on the measurement of various stressors that influence the performance and responses of a human operator. In general, a myriad of workload-assessment techniques have been proposed, and these may be classified into four broad measurement categories related to primary and secondary tasks, subjective rating, and physiological parameters (O’Donnell & Eggeemeier, 1986).

In evaluating any system or operator, one should always initially examine primary task performance with respect to the system of interest, such as measuring the speed control for driving. If the driver perceives a serious decrease in attentional capacity, then she/he can reduce the vehicle speed as a compensatory behavior to facilitate reallocation of mental resources (Brown, Tickner, & Simmonds, 1969; Patten, Kircher, Ostlund, & Nilsson, 2004). Imposing a secondary task measures residual resources or capacity not utilized in the primary task (Ogden, Levine, & Eisner, 1979), such as driving (primary task) with mathematical-additions task (secondary task). In addition, physiological data for operators are considered an additional source of information with respect to the workload imposed during various tasks. Continuous in-vehicle acquisition of driver heart rate provides an uninterrupted data set reflecting momentary changes in workload during driving. Typically, increased heart rate is associated with elevated workload (Casali & Wierwille, 1983; Lee & Liu, 2003; Wilson, 1993). Therefore, the purpose of the present study was to explore the adaptive responses of drivers in terms of coping with various workloads introduced as secondary tasks and the varying demands of altered traffic complexity.

A review of the literature reveals many studies that have examined the possible effects of concurrent cellular phone use on driving performance. The applied research methods may be categorized into the epidemiological approach, and laboratory and field study. Violanti and Marshall (1996) employed an epidemiological case-control design and logistic regression techniques to examine the association between cellular-phone use, other inattention factors, and actual traffic accidents. These workers found that talking more than 50 minutes per month on a cellular phone in a vehicle was associated with a 5.59-fold increased risk for a traffic accident. Laboratory approaches to examining the possible performance effects of driving with cellular phone use include computer games and fixed-base (Briem & Hedman, 1995; Consiglio et al., 2003; Reed & Green, 1999) and high-fidelity moving-base simulators (Alm & Nilsson, 1995). There are three primary justifications for using the driving simulator: safety; equipment cost; and, experimental control. Some research is too hazardous to be conducted in vehicles on the road (e.g., collision avoidance and the effects of alcohol). In addition, a wider variety of test conditions can be prescribed and consistently applied in a driving simulator compared to an on-road environment. It has been found, however, that performance of driving tasks (speed and lane control) is less precise in fixed-base simulators than in actual vehicles due to the lack of motion cues and proprioceptive input (Alicandri, Roberts, & Walker, 1986; McLane & Wierwille, 1975). Thus, simulators must have appropriate validity to be useful human-factors research tools. The physical validity includes the correspondence of the simulator’s components, layout, and dynamics with the real world. Behavioral validity concerns correspondence between the simulator and the real world with respect to the way the human operator behaves. On the other hand, many studies have been conducted in vehicles on the road to reflect real-world situations as closely as possible (Cooper et al., 2003; Lamble, Kauranen. Laakso, & Summala, 1999; Matthews, Legg, & Charlton, 2003; Reed & Green, 1999). Continuous research is encouraged, therefore, to provide educational and driving-safety information for road users. Thus, the present study was designed to evaluate the workload of participants while driving in real traffic environments on public motorways and urban roads. The study hypothesis was that drivers engage in compensatory behavior when performing a secondary task (i.e., cellular-phone use) in high-demand situations, attempting simultaneous reallocation of resources to preserve the required safety margins. Further, the distractive effects of cellular phone use, in terms of driving effort in variant traffic situations, were measured, taking into consideration the fluctuating workload of drivers in different conditions.

### 2. Methods

#### 2.1. Participants

Twelve participants were recruited as paid volunteers for this study. The age of the subjects ranged from 25 to 45 years, average age was 35.2 years. The sample consisted of six females and six males. All participants had held a drivers license for at least two years and drove 5,000 km or more annually. Each had owned a cellular phone for at least one year and regularly used it in vehicle. Informed written
consents and an undertaking to drive safely were obtained before commencement of the experiment.

2.2. Experimental vehicle

The experiment was conducted in an instrumented vehicle (Nissan Cefiro 3.0) with automatic transmission and a built-in, hands-free cellular phone system (Nokia 3310, Finland). Taking the inherent ethical and legal considerations into account, the experimental vehicle was distinguished from other vehicles sharing the road by an external sign that read “Experimental Vehicle,” and the parking lights were activated throughout the experiment. The vehicle was instrumented with four CCD cameras, a video-recorder system, a portable ECG system, and an auxiliary battery. The four CCD-camera system in vehicle was recording: (a) steering wheel movement and driver’s line of sight; (b) traffic; (c) vehicle’s lateral position on the road relative to the painted delineation; and, (d) driving speed from the head-up display (Fig. 1). In addition, one microphone was also mounted on instrument fascia to record driver’s verbal responses. All video and verbal signals were recorded simultaneously by a multiplex processor on a VHS recorder (Sony SL82K, Japan) for further analysis. An experimenter seated in the right-rear passenger seat operated all the test equipment.

2.3. Heart rate measurement

The driver’s physiological responses were recorded using a portable Cardiovis ECG system (Continuous 12-Lead ECG Type II PC, Cosmed, Italy). For each participant, disposable surface electrodes (Blue Sensor, VL-00-S type; Medicotest, Denmark) were placed on standard 12-leads positions (Rosen, 1988). Before the actual experiment was started, each subject was required to have a resting period of at least five minutes until his/her heart rate remained at a steady rhythm; this resting heart rate was collected to serve as a baseline measurement. During the resting period, participants were requested to sit, relax and remain silent. In practice, establishing mean heart rate for a group of subjects with respect to an entire task may be quite meaningless in view of individual differences in physical work capacity or fitness, and discrete variations in workload during a test. Thus, the incremental heart rate (difference between working and resting rates, $\Delta HR$) may be more useful for measurement of workload and establishment of maximum acceptable work limits (Kroemer & Grandjean, 1997). Therefore, heart rate was calculated from the ECG recordings by Cosmed software (Quark Windows 6.2) and data were exported into Microsoft Excel for further analysis. In addition, resting heart rate subtracted from heart rate on driving with presence/absence of phone is defined as incremental heart rate.

2.4. On-road tests

Upon arrival at the laboratory, participants were read a description of the aims of the study and given instructions with respect to the performance of the experiment. Subjects underwent training to drive while performing the experimental tasks until they were able to proceed smoothly. Participants were instructed to drive in a normal, safe manner, and to maintain a speed just below the legal limit. Driver workload was measured in two traffic situations. First, participants drove in each direction along a 7-km section of a three-lane road in Taipei city (speed limit 50 km/h) with 24 signalized intersections, and numerous buildings on both sides. In the second situation, participants drove in each direction along a 22-km section of National Highway No.3A (Taipei Connection Route) with four-lanes (speed limit 100 km/h). In addition, the experiment was conducted during off-peak daylight hours (10 a.m.–12 noon and 2 p.m.–4 p.m.). Each driver was asked to perform four of the following phone-based tasks, with their sequence also randomly determined: without (task 1) and with mathematical-addition (task 2) while driving on urban roads; without (task 3) and with mathematical-addition (task 4) while driving on motorways. The eight pairs of double-digit additions (e.g., 28+59) were relayed orally via cellular phone by a second experimenter who was seated in the laboratory. Total duration of the experiment for each participant was approximately 2.5 hours.

2.5. Measurement

(a) Driving performance: performance measurements included mean driving speed (km/h), standard deviation of steering-wheel angle (SDSW; degrees), and standard deviation of lane position (SDLP; cm).

(b) Task performance: test scores consisted of response time (sec) and proportion of correct answers (%).

(c) Physiological responses: heart rate (HR; beats/min) and incremental heart rate ($\Delta HR$, beats/min).
2.6. Data analysis

All traffic conditions were recorded so that driving maneuvers could be subsequently analyzed, with video data sampled at 3 Hz. The mean and standard deviation for all test measurements were calculated using standard statistical methods. Analysis of variance (ANOVA) was utilized to determine the effect of cellular phone use and traffic situations. An alpha level of 0.05 was selected as the minimum level of significance. Further, the relationships between driving performance and heart rate were assessed from correlation analysis.

3. Results

3.1. Number of experimental situations

The observation of 192 behaviors has been summed for situations (12 subjects × 2 traffic situations × 2 phone effect × 4 repeats). However, owing to the nature of the field study, we were not able to control the incidence of each experimental condition. Traffic jams or exceptional traffic situations were considered spurious and, therefore, were not used for data analysis. As a result, a total of 131 cases were included for analysis. Of these, 59 involved driving on urban roads with (n=31) and without phone tasks (n=28), and 72 involved motorways driving with and without phone tasks (n=36 each).

3.2. Effect of traffic situation

Analysis of variance of driving speed indicated a significant effect for traffic situation (Table 1). As expected, mean driving speed was higher on motorways (88.6 km/h) than on urban roads (45.1 km/h; F(1,127)=1482.6; p<0.001). The mean standard deviation of lane position (SDLP) did not differ significantly comparing traffic situations (F(1,127)=0.5; p>0.05). The SDLPs for motorways and urban roads were 9.1 and 9.2 cm, respectively. However, a significant difference was demonstrated for standard deviation of steering wheel movement (SDSW; F(1,127)=38.6; p<0.001). The SDSW was larger on urban roads (6.9°) than on motorways (4.1°). These results suggest that driving in urban areas is associated with higher demand for vehicle handling to adapt for complex traffic. In addition, analysis of the drivers’ physiological data reveals no significant differences in mean HR comparing traffic situations (F(1,127)=2.3; p>0.05). Further, significant differences were noted by comparing the incremental heart rate (ΔHR) between traffic situations (F(1,127)=4.2; p<0.05). Mean ΔHR was increased from 14.7 to 17.8 beats/min.

3.3. Effect of phone tasks

A significant difference in driving speed was observed with or without mathematical-addition task via cellular phone (F(1,127)=7.24; p<0.01). The mean driving speed decreased 5.8% in the presence of phone tasks in comparison to normal driving without the mathematical-addition (67 vs. 71.1 km/h). The mean standard deviation of lane position (SDLP) did not differ significantly in the presence or absence of distraction. A significant difference was demonstrated, however, in standard deviation of steering wheel movement (F(1,127)=4.6; p<0.05). The SDSW was greater in the presence of phone tasks (6.3°) than in the absence of distraction (5.1°). In addition, physiological cost was also increased with phone tasks (90.8 vs. 87.7 beats/min), and the incremental heart rate (ΔHR) while performing the secondary task was significantly higher in the presence of phone addition (17.9 beats/min) in comparison to normal driving (14.8 beats/min; F(1,127)=4.2; p<0.05). It appears that our

Table 1
Driving speed and physiological workload comparing traffic situations with or without phone task (N=131)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Speed (km/h)</th>
<th>SDLP (cm)</th>
<th>SDSW (degrees)</th>
<th>HR (beats/min)</th>
<th>ΔHR (beats/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic situations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motorway (N=72)</td>
<td>88.6*** (6.4)</td>
<td>9.1 (2.3)</td>
<td>4.1 (1.5)</td>
<td>90.9 (15.4)</td>
<td>17.8* (11.3)</td>
</tr>
<tr>
<td>Urban road (N=59)</td>
<td>45.1 (6.7)</td>
<td>9.2 (1.2)</td>
<td>6.9*** (1.7)</td>
<td>87.3 (11.9)</td>
<td>14.7 (6.6)</td>
</tr>
<tr>
<td>With/without car-phone task</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal driving (N=64)</td>
<td>71.1**</td>
<td>9.2 (2.7)</td>
<td>5.1 (2.0)</td>
<td>87.7 (13.6)</td>
<td>14.8 (9.6)</td>
</tr>
<tr>
<td>With phone task (N=67)</td>
<td>67.0 (22.7)</td>
<td>8.8 (2.2)</td>
<td>6.3* (3.1)</td>
<td>90.8 (14.2)</td>
<td>17.9* (9.2)</td>
</tr>
</tbody>
</table>

SDSW: Standard deviation of steering wheel angle.
SDLP: Standard deviation of lane position.
* p<.05.
** p<.01.
*** p<.001.

Table 2
Pairwise comparison of response time and correction rate between traffic situations (N=12)

<table>
<thead>
<tr>
<th></th>
<th>Urban road</th>
<th>Motorway</th>
<th>Mean Difference</th>
<th>t</th>
<th>df</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response Time (seconds)</td>
<td>5.55 (2.4)</td>
<td>4.96 (2.1)</td>
<td>0.59</td>
<td>2.46</td>
<td>11</td>
<td>0.03</td>
</tr>
<tr>
<td>Correct rate (%)</td>
<td>85.2 (11.4)</td>
<td>87.3 (9.9)</td>
<td>-2.11</td>
<td>-0.677</td>
<td>11</td>
<td>ns</td>
</tr>
</tbody>
</table>
participants compensated by reducing their driving speed and increasing overall physiological workload in response to the summation tasks.

In addition, the Paired-T test was used to compare phone-task performance between traffic situations (Table 2). While driving on urban roads with phone tasks, mean response time was significantly increased 11.9% (t(11)=2.46; p< .05) as compared to the motorway condition (5.55 vs. 4.96 sec). Analysis of correct-answer rate revealed no significant differences between traffic situations (t(11)= -0.677, p>.05). The mean correction rates for driving on urban roads and motorways were 85.2% and 87.3%, respectively. However, mean correction rates were worse than only mathematical-addition tests in the laboratory (90%), whether driving on urban roads or on motorways.

3.4. Heart rate versus driving speed

Profiles of heart rate and driving speed for the studied traffic situations are compared in Fig. 2. Driver heart rate was higher for motorway driving compared to the urban-road condition. Further analysis revealed that heart rate variation was associated with traffic events. For example, speed increases and overtaking other cars (event 1), and braking more intensely while approaching a red light (event 2).

All observations were further split into two subgroups as determined by traffic situation. Separate correlation-regression analyses were then run for each subgroup, with a significant difference demonstrated comparing the traffic situations. On the motorway (Fig. 3b), the correlation coefficient for the relationship between driving speed and ΔHR (r=0.63) is significant at the 0.001 level. There is a better linear relationship for driving speed and ΔHR on the motorway, and it appears reasonable that driver’s physiological workload is greatly associated with higher driving speed (above 80 km/h). In contrast, for driving on urban roads (Fig. 3a), there was more dispersion around the two measures, with analysis of linear regression not statistically significant (r=0.2, p=.15).

4. Discussion

Driving in different traffic environments induces measurable variations in driver workload. In the present study, traffic situations can be subdivided into two groups based on a taxonomic approach to information-processing demand: (a) high demand for information processing and high demand for vehicle handling (e.g., driving within city centers and complex intersections with road signs dictating right of way); and, (b) low demand for information
processing and low demand for vehicle handling (e.g., driving on motorways without intersections and with lower traffic complexity). As expected, mean driving speed was lower on urban roads, however, mean response time for phone tasks was higher than on the motorway (Fig. 4). In previous studies, Harms (1986, 1991) has also demonstrated that mean speed was lower and mean calculation time greater for drivers negotiating sections of driving routes in village areas compared to analogous highway routes, with a negative correlation determined between mean driving speed and mean calculation time. In the present study, a negative relationship has also been demonstrated between driving speed and response time for phone tasks ($r = -0.57$). This result is consistent with the assumption that dual-task performance decrements are due to increases in task complexity.

Indeed, driving in urban areas with complex traffic environments (i.e., varying density of traffic signs, traffic flow patterns, and number and type of road users) induces a higher mental workload for drivers (Harms, 1991). On the other hand, cardiovascular parameters, such as heart rate, vary in relation to the type of road environment (Richter, Wagner, Heger, & Weise, 1998). Hasbrook and Rasmussen (1970) have indicated that increased G-forces are probably the reason for the increase in cardiovascular workload during take-off and landing maneuvers. Since heart rate is strongly associated with G-force stress, HR and $\Delta HR$ were increased during high-speed driving in the present study. The main component of driving workload may vary between traffic situations, and the physiological component, which is associated with driving speed, is the main contributor on the motorways.

Continuous vigilance is required to rapidly detect and respond to any changes that may suddenly occur in traffic, and for dynamic driver resource reallocation or adjustment of performance in accordance with changing workload. Hancock and Warm (1989) have proposed three fundamental states of performance: (a) stable, typified by driving in normal, non-challenging conditions; (b) transient, where the demands of the environment are sufficient to tax the adaptive capability to its limits (e.g., sudden onset of traffic congestion prompts the driver to cease conversation and focus exclusively on the road); and, (c) additional demands to the transient state precipitate onset of a failure state where performance level decreases rapidly (Hancock, Simmons, Hashemi, Howarth, & Ranney, 1999). Normal motorway driving is stable state, while driving in urban areas is transient. Task demands for driving are variable, however, and at times the driver may be left with considerable spare capacity, which can be utilized for undertaking unexpected tasks (Lansdown, Brook-Carter, & Kersloot, 2004). When additional demands occur in the transient state, however, such as receiving a phone call in heavy traffic, the failure state may occur immediately, with drivers becoming overloaded and/or distracted by the additional information and subsequently taking increased risks.

5. Conclusions

Results of the field study show that despite the facts that tasks can be performed on a high level when carrying out a number of them concurrently (i.e., driving with cellular phone), drivers should be attempting to avoid the high associated cognitive overheads by either adapting their driving behavior or by skipping the subtasks (Cnossen, Rothengatter, & Meijman, 2000). Cellular phone-related distraction increases risk, however, and mobile telephone use is associated with reduced headway with respect to vehicles, and significantly greater brake pressure being applied on urban roads (Lansdown et al., 2004). As greater on-road workload, directly analogous to any increased momentary demands, are imposed on the driver, the number of available resources and associated safety margins are reduced. Where successful responses are not sufficient for safe driving, the driver incurs increased risk of accident. The results of this field study confirm the findings of analogous investigations and, thus, it is recommended that drivers do not engage in cellular phone use while driving under any circumstances in urban areas. On the other hand, drivers should be very careful while engaging in cellular phone use on the motorways, particularly during potentially critical situations (e.g., overtaking, traffic congestion). A greater safety margin should, therefore, be maintained (e.g., via lower driving speed and increased headway) and, in real-world situations, it can be assumed that there is a trade-off between tasks in terms of processing demand to preserve driving safety.

Acknowledgements

This study is supported by a grant from the National Science Council of Taiwan (Project No. NSC 91-2213-E-011-063). The authors also wish to acknowledge the Asian Technical Center of Yulon Motor Co. Ltd. for providing the experimental vehicle.

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