VISUAL DEMAND OF DRIVING AND THE EXECUTION OF DISPLAY-INTENSIVE IN-VEHICLE TASKS

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ABSTRACT

To gain insight as to when telematics can be distracting, 16 participants drove a simulator on roads with long curves of several different radii. Participants read electronic maps displayed in the center console while both parked and driving. In separate trials, the visual demand/workload of the same straight and curved sections was measured using the visual occlusion technique. Visual demand was correlated with inverse curve radius.

As visual demand increased, driving performance declined. Participants made shorter glances at the display, made more of them, but waited longer between glances. Overall, task completion time increased when the task was performed while driving (versus while parked), except for short duration tasks (a single glance or under 3 seconds timed while parked), where task time decreased. While driving, task completion times were relatively unaffected by the driving workload.

INTRODUCTION

Recently, there has been a proliferation of in-vehicle telematics systems and functions. This proliferation should continue into the future (Richardson and Green, 2000), though to a large degree, continued growth depends upon successfully addressing concerns of the safety and usability of telematics. The performance of telematics tasks while driving must be examined and understood in detail. Important aspects include minimizing the distraction potential of the interfaces to telematics and managing information flow to the driver (Michon, 1993). These topics have been the focus of considerable prior research (e.g., Wierwille, Antin, Dingus, and Hulse, 1988; Parkes and Franzen, 1993; Noy, 1997; Wakita, and Terashima, 1999).

This paper describes the second in a series of studies to identify the effects of the visual demand of driving on in-vehicle task performance and associated driving performance. In contrast to other research, this series has quantified the visual demand of driving using the visual occlusion technique (Senders, Kristofferson, Levison, Dietrick, and Ward, 1967). In its simplest form, participants drive and close their eyes as often as possible. The fraction of time their eyes are open indicates the visual demand of a road segment. In the first study of this series (Tsimhoni and Green, 1999) participants pressed a switch to request 500 msec glimpses of the road (a typical glance duration), a procedure easier to implement than monitoring eyelid closure. The key finding of the study was a linear relationship between the mean visual demand for a curve (the fraction of time the road was visible) and the inverse radius of curvature.

The current study (Tsimhoni, Yoo, and Green, 1999) builds upon findings and methods from the previous study using long constant radius curves to provide stable and measurable levels of visual demand while drivers perform in-vehicle tasks, namely reading maps. The following questions were addressed:

1) How does the visual demand of driving affect driving performance while concurrently completing a display-intensive in-vehicle task?
2) How does visual demand affect the time to complete the in-vehicle task?
3) How do visual demand and task duration affect glance behavior?

TEST PLAN

Test Participants

Sixteen licensed drivers participated in this experiment, 8 younger (21-28 years old, mean of 25) and 8 older (66-73 years old, mean of 70). Within each age bracket there were 4 men and 4 women. Participants were recruited via an advertisement in the local newspaper and from the UMTRI participant database. All were paid $35 for their participation.

Test Activities and their Sequence

Participants completed 3 different map-reading tasks with 3 mean durations (short, medium, and long) under 5 different driving workload levels (parked, straight road, easy curve, moderate curve, and sharp curve). All participants participated in all conditions.

After completing a biographical form, consent form, and a vision test, participants were seated in a driving simulator. They were familiarized with all street names and icons that would appear on the maps and the 3 types of questions about maps to be answered. The test activities and their sequence are summarized in Table 1.

Table 1. Summary of test activities and their sequence

Test activity		Time [min]	Maps
Map reading	Training	16	24
	Baseline 1	5	12
Driving	Training	5	
	Baseline	16	
Driving and map reading	Training	8	12
	Test block 1	16	24
	Test block 2	16	24
	Break	5	
	Test block 3	16	24
Map reading	Baseline 2	5	12
Driving with visual occlusion	Training	10	
	Test block 1	16	

Test Materials and Equipment

The experiment was conducted using the UMTRI Driver Interface Research Simulator, a low-cost driving simulator based on a network of Macintosh computers [http://www.umich.edu/~driving/sim.html]. The projection screen, offering a field of view of 33 degrees horizontal by 23 degrees vertical, was 6 m (20 ft) in front of the driver, effectively at optical infinity.

Test roads (2 lanes, 3.66 m [12 feet] wide) consisted of 1 straight test section and curves with 3 different radii, connected by short straight sections, for which data were not collected. The straight section and 3 curve radii (582 m, 291 m, and 194 m; or 3, 6, and 9 degrees of curvature, respectively) were identical in width and radius to those in Tsimhoni and Green (1999). Since Tsimhoni and Green found visual demand to stabilize at approximately 150 m past the curve entry point, the map-reading task of this study was initiated 200 m after the entry point. To provide a constant workload of sufficient duration for all tasks in each block (80 s), the test curves were longer than in the prior research.

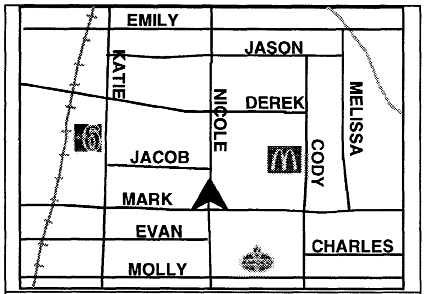
The apparatus for occluding the road-scene consisted of a switch, mounted on the participant's index finger and connected to the driving simulator. In blocks that assessed the demand of driving, a gray screen replaced the simulator scene for 500 ms whenever the switch was depressed. In blocks that involved reading maps while driving, pressing the switch turned on the map display and replaced the road scene with a gray screen for as long as the switch was depressed (except for a control condition in which the road scene was not grayed out to examine if any road information was absorbed when drivers were looking inside the vehicle at a map).

To simulate a 16 cm (6.25 in.) diagonal monitor (4:3 aspect ratio), the electronic maps were displayed on an unmasked portion of a 13 in. color monitor mounted in the center console of the simulator cab. The center of the monitor was positioned 27±2 degrees below the horizontal line of sight and 28±2 degrees to the right of the center.

In the map-reading task, participants verbally responded to questions about maps shown on the center console. Questions and their responses were grouped into 3 duration categories (short, medium, and long, approximately 2, 4, and 8 s) (Figures 1 and 2). Each map consisted of 12 streets (6 horizontal and 6 vertical), 1 river, and 1 railroad track. The street names were taken from a list of 100 most popular first names in the U.S. The 16-point font translated to 17 min of visual angle (0.005 radians), consistent with results from Nowakowski & Green (1998), which recommended 14-point text for similar map displays viewed at a similar distance.

Also appearing on the maps were 9 icons from 3 categories (hotels, fast food restaurants, and gas stations) likely to be found on real maps. The icons were chosen so that they were familiar to U.S. drivers and were easily discriminated. The participants practiced identifying the icons and their corresponding categories prior to the actual trials.

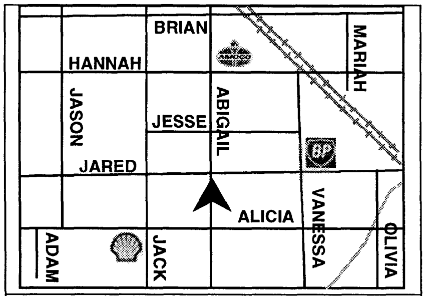
Thus, the map reading task involved reasonable questions that could be asked while driving. It used stimuli that were legible, understood by drivers, and representative of real in-vehicle maps in terms of their size, location, and content. This task was performed in a driving simulator whose dynamics and cab were reasonable for a real vehicle, using roads whose geometry was reasonable for real roads.



Short Duration Task:
"What street are you on?" (Nicole)

Medium Duration Task:
"what street is the fast food restaurant on?" (Cody)

Figure 1. Example of map for short and medium tasks
Note: The same map graphic could be used for either question.



Long Duration Task:
"What street intersects with Vanessa at a gas station?" (Jared)

Figure 2. Example of map for long task

RESULTS

Driving Performance

For each block in which participants performed the map-reading task while driving, 12 samples of 5 s of driving data were analyzed (1 sample for each map). The sampled section began after the question had been asked and ended 5 s later. For the driving baseline and the occlusion blocks, the sampled section began at the same location in the curve where the question would be asked and ended 5 s later. (An interval of 5 s was chosen as a compromise that allowed comparison between tasks of different durations.)

Figure 3 presents the standard deviation of lateral position (sampled at 30 Hz) in the 3 tested conditions. In the driving baseline, the variability in lateral position increased by 75% as a function of curvature. The pattern of driving performance as a function of curvature while performing the secondary task was similar but the magnitude was 80% higher. Interestingly, driving performance in the visual occlusion condition and while performing the secondary task was essentially identical.

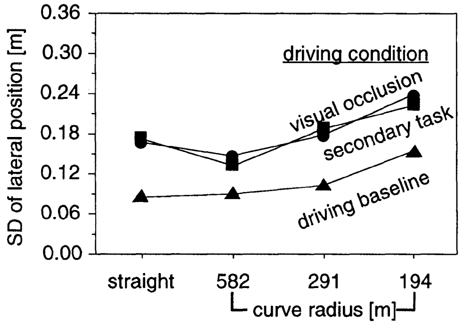


Figure 3. The effect of curvature on the variance of lane keeping

The rate of lane departures followed a different pattern. For the secondary task condition, the rate increased from no departures on straight sections to approximately 1 departure per minute on the sharp curve. In the driving baseline it remained 0, but in the occlusion block (no secondary task), it decreased from about 1.5 departures per minute on straight sections to essentially no departures on the sharpest curves.

The Effect of Driving on Task and Glance Measures

The 7 task- glance- and driving-related dependent measures shown in Table 1 were examined in this experiment.

Table 2. Dependent measures and their definitions

Measure	Definition
Task completion time	Time required to complete the task, from the beginning of the first glance at the display to the end of the last glance
Number of glances	Number of glances at the display to complete the task
Mean glance duration	Mean amount of time the participant depressed the key to view the display
Total glance duration	Cumulative time elapsed glancing at the display during all glances; total eyes-off-the-road time
Mean time between glances (For >1 glances)	Cumulative time elapsed not looking at the display divided by the number of glances away from the display
Visual demand (VisD)	The percentage of time the road was viewed (not occluded) using the voluntary occlusion technique
Lane departure	Any part or whole of any tire is outside the lane boundary

On average, task completion time increased from 3.6 s to 4.7 s (+30%) when the task was performed while driving ($p<0.0001$) as shown in Figure 4. This increase reflects the need to spend time attending driving and transitioning between the display and the road. Also found was a 3-way interaction between the effect of driving, the task duration, and the participant's age ($p<0.001$), with younger drivers taking less time to complete the short task while driving than when parked and with older drivers taking equal time. This is probably due to time pressure to complete the task as soon as possible when driving (i.e., to look back at the road).

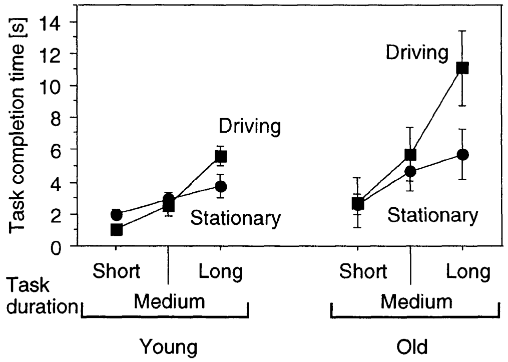


Figure 4. Task completion time by task duration and age

For these tasks, the total glance duration (total eyes-off-the-road time) was significantly shorter when driving (2.9 vs. 3.5 s, $p<0.0001$), and more so for shorter tasks.

The Effect of Curvature on Glance Measures

Overall, task completion time was not significantly affected by curvature, although other glance measures were affected. As curves became sharper (visual demand increased), mean glance duration decreased from 1.8 s on straight sections to 1.2 s on 194 m radius curves ($p<0.0001$). This effect was greater for longer tasks ($p<0.05$, Figure 5A). Accordingly, the number of glances increased as curves became sharper ($p<0.05$), but only for the long duration tasks. It increased from 2.6 ± 1.4 on straight roads to 3.5 ± 1.2 on the sharp curves. Since the decrease in mean glance duration was relatively greater than the increase in the number of glances, total glance duration (the product of mean glance duration and the number of glances), decreased as curves became sharper ($p<0.001$). Finally, the mean time between glances significantly increased as curves became sharper ($p<0.001$, Figure 5B). In longer tasks, it increased from 1.1 s to 1.8 s.

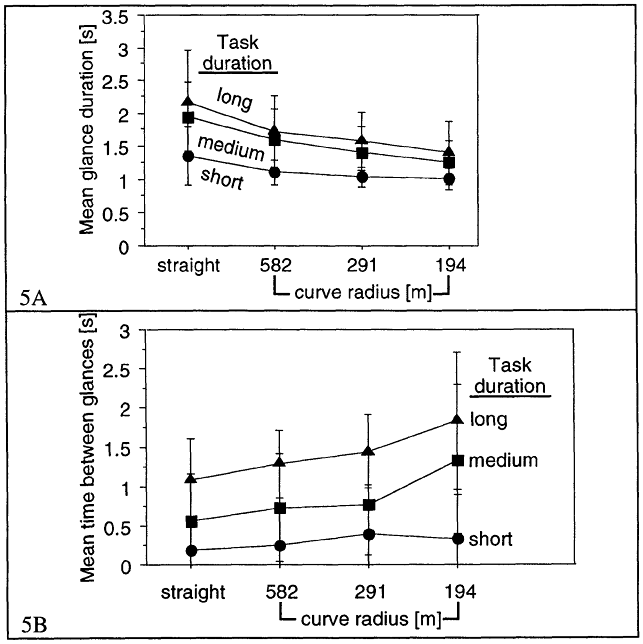


Figure 5 [A-B]. The effect of curvature by task duration on [A] mean glance duration and [B] mean time between glances

Voluntary Occlusion

As in previous visual occlusion studies, visual demand in this study was linearly related to road curvature. Equation 1 shows a linear regression relationship between visual demand and the reciprocal of curve radius in this experiment. The mean visual demand value was 25% on straight roads and 43% on sharp curves.

$$\text{VisD (w/o the beginnings of curves)} = 0.252 + 34.5 * 1/r \qquad (1)$$
$$\text{(r=curve radius)} \qquad R^2 = 0.98$$

Higher visual demand of driving in sharper curves resulted in a decrease in mean glance duration. When the visual demand of driving increased, the participant could not afford to look away from the road for long periods of time. Therefore, there was a need to shorten the mean duration of glances. Accordingly, the mean glance duration of long tasks decreased as a function of curvature (R^2 = 0.18, Figure 6A). The amount of variance explained (R^2 = 0.34, Figure 6B) doubled when individual differences were included (using the individual visual demand values from the visual occlusion measurements) instead of the curve radii.

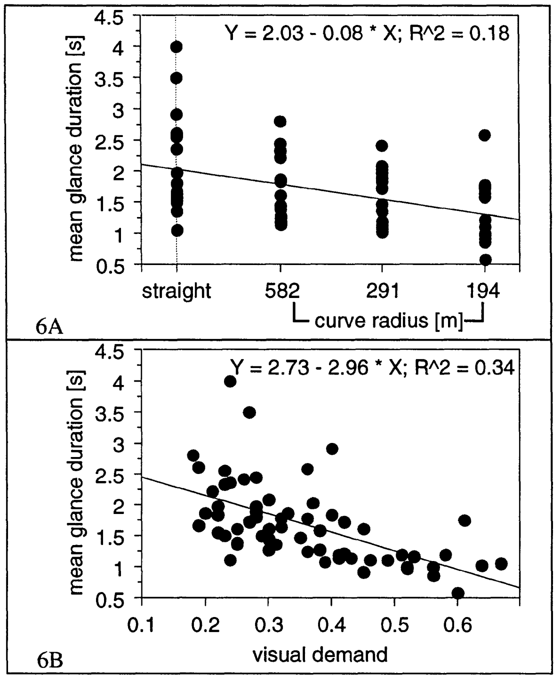


Figure 6. Regression of mean glance duration (long task) by [A] curvature and by [B] visual demand

KEY FINDINGS AND DISCUSSION

1. Adding a secondary task significantly degraded driving performance. Drivers wandered more in their lane and departed from their lane more frequently. The increase in the standard deviation of lane position was approximately 80%.

2. Driving performance while not looking at the road some of the time (the occlusion condition) was similar to driving performance while looking inside the vehicle to perform a task for an equivalent period of time.

3. Task completion times were generally, but not always, longer while driving than when parked. Overall, the increase was from 3.6 s while parked to 4.7 s (+30%) while driving. Short duration tasks (a single glance or under than 3 s) were performed faster while driving than when parked. In contrast, for long tasks, task completion times increased when driving (from 3.8 s to 5.7 s, +50%, for young participants and from 5.6 s to 11 s, +96%, for old participants).

4. Task completion times while driving were relatively unaffected by the visual demand of driving. The conventional wisdom is that when workload increases drivers stretch out tasks. In these data, there was no increase in task completion time between the different curvature levels. A slight increase in task completion time from 8 s to 9 s occurred in the highest workload curve on the "long" tasks. Persistence seems to be the best description of how drivers completed a task. Once started, drivers continued to switch between driving and the in-vehicle task without interruption. The reasonably stable workload levels may have encouraged such behavior.

5. Increasing visual demand decreased the duration of in-vehicle glances, increased their number, and increased the time between they were made. The decrease in in-vehicle glance durations was about 33%. This was because long glances away from the road were particularly problematic when visual demand was highest. The increase in the time between glances was about 60%.

6. Total glance time (total eyes-off-the-road time, the product of number of glances and their durations) decreased with visual demand. For short tasks the decrease was from 2.3 s to 1.4 s, -39%.

7. Predictions of mean glance duration were improved by using individual demand data rather than just curvature. The variance that was accounted for increased from 0.18 to 0.34.

The big picture of how drivers respond to increasing visual demand was similar in some ways to what was assumed at the beginning of this experiment, different in others. As the visual demands of driving increased (as characterized by the occlusion method), drivers responded by making shorter glances, but more of them. So, the total glance time remained constant, or slightly decreased. Additionally, as the demand of driving increased, so did the time between glances inside the vehicle. What was surprising was that for brief tasks, glance durations were <u>less</u> while driving. Moreover, there was very little change in task completion time as the visual demand of driving increased. Some stretching was expected, and while it did occur, the effect was not significant. What did occur, however, was a significant degradation of driving performance. This degradation occurred even though drivers compensated for increased visual demand by decreasing their eyes-off-the-road time. Thus, these data show that drivers do not fully compensate for the demands of a telematics application by maintaining an appropriate level of driving safety. In other words, risk homeostasis is not maintained.

Reflection upon the data raises 4 explanatory factors that should be examined in future studies:

(1) *Time pressure* - due to the time pressure to look back at the road, some tasks were performed more quickly when driving, thus reducing the total glance duration.

(2) *Postponed processing and planning* - while driving, some of the processing time must have occurred when the participant was not looking at the display, thus reducing the total glance duration.

(3) *Interference* - while driving, some attention might have been allocated to the driving task even when the in-vehicle task was performed, thus increasing the total glance duration.

(4) *The cost of partitioning* - longer tasks required multiple glances, thus forcing some executive overhead as well as some reprocessing time due to forgetting and the need to reacquire the last point of gaze. The increased cost of task partitioning and possible interference between the tasks partially negated the effects of postponed processing and time pressure.

Readers should bear in mind that these findings pertain primarily to visually-intensive tasks of relatively short total duration (under 10 s while driving) performed in situations of low to moderate stable visual demand (25%-50% as measured by visual occlusion). Extension of these findings to longer and more interactive tasks (e.g., destination entry) should be based on further experimental work.

This experiment has several implications for both researchers and telematics designers:

First, in future experiments that study glance behavior while driving, the levels of visual demand imposed by the driving task when the in-vehicle task is performed should not be ignored. As shown in this experiment, even moderate changes in driving workload have significant effects on the timing of glances.

Second, when predicting task completion times from stationary times in very short tasks (under 3 s), a decrease may be expected. In the current experiment, only for longer tasks of 4 s or more was there an increase, whose rate tended to relate to the length and difficulty of the task.

Third, some have suggested an occlusion procedure for the in-vehicle display (with no time limit on the task) for deciding whether an in-vehicle task is acceptable for driving. The logic behind this claim is that if a task can be partitioned successfully into short viewing times, drivers can perform it safely. The current data, collected using driver-initiated voluntary occlusion, show degradation in driving performance when performing tasks while occluded or when performing in-vehicle tasks of similar visual demand, even for tasks of very brief duration. This calls into question the merits on an occlusion-based test protocol with no time limit as an alternative to the 15-second total task time limit in SAE J2364 (Society of Automotive Engineers, 2000). Further, these findings are counter to the claim that if a task is partitionable into small pieces then there is necessarily no risk to the driver. Nonetheless, debates of modifications of J2364 are likely to continue. Stay tuned.

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REFERENCES

George-Maletta, K., Hunter, D.R., Brooks, A., Lenneman, J., and Green, P. (1998). Preliminary Examinations of the Time to Read Electronic Maps: The Effects of Text and Graphic Characteristics, (Technical Report UMTRI-98-36), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Michon, J.A. (1993) Generic Intelligent Driver Support, London, U.K.: Taylor and Francis.

Nowakowski, C. and Green, P. (1998). Map Design: An On-the-Road Evaluation of the Time to Read Electronic Navigation Displays (Technical Report UMTRI-98-4), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Noy, Y.I (ed.) (1997). Ergonomics and Safety of Intelligent Driver Interfaces, Mahway, NJ: Lawrence Erlbaum Associates.

Parkes, A.M., and Franzen, S. (eds.) (1993). Driving Future Vehicles, London, UK: Taylor and Francis.

Richardson, B. and Green, P. (2000). Trends in North American Intelligent Transportation Systems: A Year 2000 Appraisal (Technical Report UMTRI-2000-9), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Senders, J.W., Kristofferson, A.B., Levison, W.H., Dietrick, C.W., and Ward, J.L. (1967). The Attentional Demand of Automobile Driving, Highway Research Record #195, Washington, D.C.: National Academy of Sciences, Transportation Research Board, 15-33.

Society of Automotive Engineers (2000). Navigation and Route Guidance Function Accessibility while Driving (SAE Recommended Practice J2364), version of January 20, 2000, Warrendale, PA: Society of Automotive Engineers

Tsimhoni, O. and Green, P. (1999). Visual Demand of Driving Curves Determined by Visual Occlusion, paper presented at the Vision in Vehicles 8 Conference, Boston, MA, August 22-25.

Tsimhoni, O., Yoo, H., and Green, P. (1999). Effects of Workload and Task Complexity on Driving and Task Performance for In-Vehicle Displays As Assessed by Visual Occlusion (Technical Report UMTRI-99-37), Ann Arbor, MI: University of Michigan Transportation Research Institute.

Wakita, T. and Terashima, R. (1999). Visual Behavior model for navigation System Operation while Driving. Proceedings of the Sixth World Congress on Intelligent Transport Systems (CD-ROM), Washington, D.C., ITS America.

Wierwille, W.W., Antin, J.F., Dingus, T.A., and Hulse, M.C. (1988). Visual Attentional Demand of an In-Car Navigation Display System, in Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P., and Taylor, S.P., (eds.), Vision in Vehicles II, Amsterdam, Elsevier Science, 307-316.