Effects of e-map format and sub-windows on driving performance and glance behavior when using an in-vehicle navigation system

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Abstract

An on-road driving experiment was conducted to investigate the effects of e-map format and sub-windows on driving performance and glance behavior of navigation system users. Twenty-eight participants navigated an urban route using the navigation display with 2D or 3D e-maps and either with or without sub-windows. Driver navigation errors and visual glance data were gathered during the trials. The analytical results demonstrate no significant difference in driving performance between the 2D and 3D e-map conditions. However, use of a 3D e-map was associated with significantly more frequent glance behavior than the 2D display. Furthermore, subjects using the navigation display with a sub-window made significantly fewer navigation errors (50% less) compared to those using the navigation display without a sub-window. This investigation suggests that performance improves when using sub-windows. Finally, this study discusses wider implications in the design and use of navigation displays.

Relevance to industry

We found that the e-map format is related to driver glance behavior when using an in-vehicle navigation display. The sub-window also provides substantial influence on driving performance and glance behavior. The results of our study will assist in designing in-vehicle navigation systems and improving the performance of navigation e-maps for path-finding tasks.

Keywords: Display; interface design; driving performance; visual demand; map
1. Introduction

The recent advances in global positioning systems (GPS) have resulted in automobile manufacturers producing intelligent transportation systems to assist drivers. These systems often include in-vehicle navigation systems. Navigation systems combine an electronic map (e-map) and permanent roadway signs to visually or aurally inform drivers of their current location and of relevant traffic information. These signs provide a technological solution to the problems associated with driver navigation in unfamiliar areas. While these systems benefit drivers by providing route guidance information and traffic status, drivers must adapt to simultaneously handling a larger visual load. Additionally, when receiving system information, drivers must divert their eyes from the road, a practice that seriously impacts driving safety. Distraction from the primary driving task is one of the most common causes of traffic accidents (Wierwille, 1995). Accordingly and optimally, the amount of information presented to drivers, including all distractions, should not exceed their information processing capacity (Bendak and Al-Saleh, 2010). Previous studies have also reported that the increased visual demand associated with using a navigation system can negatively impact driving safety and performance (Ross and Burnett, 2001; Toshiaki, et al., 2003; Williams and Helbig, 2006). Therefore, a major requirement in display-based navigation systems is the rapid and reliable transmission of easily understandable information (Baumann, et al., 2004; Ma and Kaber, 2007).

Vision is the most important sense for the human, through which he or she receives 90% of the environmental information (Jung and Kee, 1996; Masih-Tehrani and Janabi-Sharifi, 2008). Thus, drivers prefer navigation systems in which route
information is represented via a graphical visual display although auditory displays have received relatively low workload ratings (Liu, 2000; Streeter, et al., 1985). Furthermore, under complex driving conditions, drivers may have greater difficulty in filtering and remembering useful information presented using an auditory display, largely owing to the problem of memory interference (Liu, 2000). To date, the moving e-map remains the primary medium for navigation and GPS applications (Sikanen, et al., 2005). Further, it is unlikely that the visual e-map will ever be completely replaced by voice guidance. Therefore, incorporating a well-designed human-machine interface (HMI) into in-vehicle visual displays is an essential addition that will improve driving performance and reduce the duration of glances to the display.

The e-map presentation format has been refined from a two-dimensional (2D) to a three-dimensional (3D) format (Van Orden and Broyles, 2000). As the world exists in 3D, the 3D format more closely represents the ‘real world’, implying better human perception and performance. However, previous investigations have found that 3D displays are not markedly superior to 2D displays for air combat or air traffic control tasks (Tham and Wickens, 1993; Van Orden and Broyles, 2000). These studies largely focused on pilot and air traffic controller performance, and few studies have attempted to evaluate differences in driving performance when using the 2D or 3D formats. It is necessary to assess the influence of e-map format on driving performance and visual demand while using a navigation display.

Recently, multi-window interface technology has enabled navigation displays to simultaneously represent to both a main-window and a sub-window. The sub-window is generally designed to highlight information on turn direction (i.e., present the region of an upcoming intersection in large scale next to the main window) when approaching an
intersection. By combining a main-window with a sub-window, the navigation display provides noticeable and redundant route guidance for driver decision-making, possibly resulting in better navigational performance than a single-window display. However, an additional sub-window may increase the visual demands imposed on the user. The effect of sub-windows on driving performance remains poorly understood, since most navigation-related studies have only examined single window displays (Liu, 2000; Streeter, et al., 1985; Sikanen, et al., 2005; Van Orden and Broyles, 2000). Further, the interaction between sub-windows and driver distraction remains unclear.

Many countries have not yet implemented regulations to ensure safety in the use of in-vehicle navigation systems. It is important to understand which navigation display representation formats can safely and efficiently assist drivers, particularly when navigating in a compact city with numerous intersections. To obtain more reliable evidence regarding the effects of e-map format and sub-windows, we performed a controlled on-road driving experiment, as opposed to the more common simulated driving trial in a virtual environment (Eoh, et al., 2005; Godwin, et al., 2008; Godwin and Eger, 2009). This study attempts to investigate the extent to which drivers benefited from the inclusion of 3D representations and sub-windows in a navigation display. This study used two key benchmark comparisons: (1) driving performance and glance behavior with and without a sub-window, and (2) driving performance and glance behavior using a 2D e-map format compared to performance and glance behavior using a 3D format for navigation purposes.

2. Methods
2.1. Subjects

In the first stage, 35 young male adults with mean age of 26.4 (±3.6) years were recruited as candidate subjects. All candidate subjects satisfied the following criteria: clean driving license; regular drivers for at least the previous three years; unfamiliar with the study area; no previous use of an in-vehicle navigation system; normal (20/20) or corrected to normal visual acuity and normal color vision. Previous studies have shown that navigation ability potentially influences driving performance, driving behavior and/or information preference (Allerton, 2000; Burns, 1998; Streeter and Vitello, 1986). In order to compensate for differences in the navigation ability of the test subjects, candidate subjects were tested for map-reading ability using an e-map displayed on a computer screen. Specifically, the 35 candidate subjects were asked to identify a feasible path to a destination from a given starting position. Candidate subjects were instructed to record the street names and turn information for the identified path as quickly as possible. Task completion time and accuracy were combined as a total score for the map-reading test. Ultimately, 28 participants passed the baseline of the map-reading test with similar performance scores were recruited as formal subjects. The aims of this study were explained in detail to all participants before the driving trial. Upon completion of the on-road driving trial, subjects were compensated for their participation.

2.2. Apparatus

The on-road driving experiment was performed in a mid-size automobile (Ford...
Two PC cameras (Logitech QuickCam Messenger) were used to monitor driver responses and road conditions. Each PC camera captured 30 frames per second and was connected to a notebook computer for data processing. The MIO Moov series of navigation systems with the MioMap software were used to provide the study participants with moving e-maps and visual turn instructions. The navigation system is capable of presenting either the 2D-‘plan’ view (vertical top-down route view) or the 3D-perspective e-map. In addition to the e-map, the system displayed a moving direction arrow, distance to the next turn, the name of the current road and the name of the road onto which the participant would be turning. The application software was run on the Win CE.Net 4.2 platform using a Samsung 400 MHz processor and 64MB RAM. The navigation system incorporated a 3.5-in diagonal TFT-LCD screen with a resolution of 320 horizontal pixels by 240 vertical pixels.

2.3. Experimental design

2.3.1. Independent variables

This work assesses two independent variables: e-map format and presence of a sub-window. The e-map format was a between-subject factor and included either 2D or 3D e-maps to represent the navigation route on the display. The presence or absence of a sub-window was also a between-subject factor with two levels, no sub-window or one sub-window. Four experimental conditions (2 × 2) were generated from the combination of the e-map format and sub-window variables. The test navigation system was set to display each experimental condition, as illustrated in Fig. 1. Twenty-eight
subjects were carefully divided into four equal-sized groups, with age, map-reading ability and years as a licensed driver balanced between the groups. Each group was then assigned to one of the four experimental conditions.

2.3.2. Dependent variables

Dependent variables related to driving performance and visual glance behavior were captured. All navigation errors were recorded by the observer accompanying each subject during the driving trial. Navigation errors were defined as situations where a subject took a wrong turn or missed a turn while following the directional advice of a navigation system during the trial. This study focused on the possibility that the different experimental conditions influenced the number and magnitude of subject navigation errors during the driving trials. Generally, it is agreed that the number of navigation errors provides a good measure of driving performance when using a navigation system (Burns, 1998; Liu, 2000; Ma and Kaber, 2007; May, et al., 2005).

Visual glance behavior was measured with a digital video camera to determine glance duration and the number of glances targeting the in-vehicle visual display during the driving trial. The glance duration was defined as the fixation time plus the transition time between the display and road. Glance duration was estimated by replaying the recorded video in Windows Media Player 9.0. The replay speed was set to 1/30 of the normal speed. We carefully watched the slow-motion video and recorded the durations of glances for each subject. The mean glance duration was derived by averaging all glance durations throughout the driving trial for each subject. The glance duration and number of glances were considered as key indicators of driving distraction (Chiang, et
al., 2004; Green, 1999; May, et al., 2005; Zwahlen, 1988). Longer glance duration and larger numbers of glances at the in-vehicle display are assumed to indicate higher levels of distraction, with a potentially negative impact on driving safety.

2.3.3. Experimental route

The chosen experimental route was located in downtown Changhua, a county in Taiwan. The route was designed to include five driver decision points throughout the 2.3 km length, as illustrated in Fig 2. Table 1 lists the characteristics of the five decision points. A driver decision point was defined as a location where a driver was provided with more than one navigation choice and was not following a main artery. These decision points were locations where failure to observe navigational instructions could lead to a driver navigation error. The route took about 10 min to drive and was performed on roads with a speed limit of 50 km/h.

2.3.4. Controlled factors

The navigation display was placed in a stationary position just above the mid-console during all experimental trials. This positioning was chosen because the onboard display position affects driving performance when using an in-vehicle navigation system (Wittmann, et al., 2006). The voice guidance function of the test navigation system was disabled during the driving trials. Voice guidance stimulus is a powerful coding dimension and is excluded from the scope of this study.

Owing to the constraints of driving an actual route with a real navigation system, it
was impossible to maintain identical traffic conditions for all trials. To maintain similar traffic conditions, all trials were conducted on weekdays in either the morning (9:30-11:30am) or the afternoon (1:30-3:30pm). Furthermore, the trials took place only in good weather and on dry roads to maintain good visibility and driving safety.

2.4. Experimental procedure

Before each trial, subjects confirmed that they had not taken any medication, alcohol or coffee during the previous 24 hours. To familiarize subjects with the vehicle controls, they were asked to freely drive the car for approximately 20 min, without the use of the navigation system. The practice driving route was different from the study route. The subjects were then asked to drive from a starting position to a pre-identified destination using the navigation system under one of the four experimental conditions. The subjects were instructed that their primary task was to reach the destination while driving safely and following the navigation instrument. The navigation system provided subjects with correct turn information as they approached each decision point. The driving route required each subject to make five turns in order to reach the destination. Subjects were told that there was no hurry to complete the trial and that their driving speed should not exceed 50 km/h. The observer, seated in the front passenger seat, recorded driver navigation errors. For example, if the navigation system advised the driver to turn right at a decision point but the driver instead turned left, an error would be recorded. When the driver made an error at a decision point, the experimenter would immediately ask them to return to that decision point and continue performing the trial. All driver reactions were videotaped during the trial. The entire procedure took approximately 40
minutes, including the 20-min practice, the 10-min transition from the practice route to the study route, and the approximately 10-min driving trial.

2.5. Data analysis

The descriptive statistics included analysis of the means and standard deviations for each dependent measure. The data distributions for each dependent measure were tested against normality using the Kolmogorov-Smirnov Goodness-of-Fit test. The level of significance was set at $p < 0.05$. Furthermore, analysis of variance (ANOVA) was applied to determine whether the e-map format or presence of a sub-window impacted the dependent variables ($a= 0.05$). If the respondent data distribution was abnormal, the Mann-Whitney procedure (non-parametric counterpart of the two-sample t-test) was used to evaluate the main effects of interest ($a= 0.05$). If the analytical results revealed null findings, a post hoc power analysis would be conducted to assess whether the null findings were simply the result of small group size.

3. Results

Table 2 lists the descriptive statistics (mean and standard deviation) and normality testing results for each dependent variable under the four experimental conditions. All $p$-values obtained from the Kolmogorov-Smirnov Z test exceeded 0.05, supporting the normality assumptions for the analyses of variances (ANOVARs). Table 3 lists the ANOVA results and shows that the influence of sub-window presence was significant ($p < 0.05$) for all three dependent variables. Furthermore, the e-map format effect was
only significant for number of glances, and the interaction effect between e-map format and sub-window presence did not significantly affect any of the dependent variables.

Because no significant differences were found in navigation error count and mean glance duration between use of the 2D and 3D displays, a post hoc power analysis was conducted. We determined that the null hypothesis should be rejected with a high probability if the difference in mean error count between 2D and 3D displays was as high as 1.7, which was slightly greater than the standard deviation of error count (nearly 1.5). Given \( n = 7 \) (sample size), a \( \beta \) risk of about 0.19, or approximately an 81 percent, of statistical power was obtained. For the data regarding mean glance duration, the power analysis indicated an approximately 82 percent chance (statistical power) of rejecting the null hypothesis if the difference in mean glance duration between the use of 2D and 3D displays was at least 0.6 sec, slightly greater than the standard deviation of glance duration (nearly 0.5). In summary, we believe that the null findings are not simply the result of small group size, as our experiment was able to detect a reasonable departure from the null hypothesis.

3.1. Number of navigation errors

A significant effect of the presence of sub-windows was observed on error count (number of navigation errors), as shown in Table 3. The difference in error count between the presence and the absence of a sub-window is shown in Fig. 3. Clearly, when the sub-window was present, subjects made significantly fewer errors, roughly half as many compared to the case without sub-windows. Thus, we conclude that the presence of a sub-window clearly improved driving performance. The e-map format
effect and the effect of the interaction between the e-map format and the sub-window were insignificant in terms of number of navigation errors.

3.2. Mean glance duration

Experimental data also indicate that the presence of a sub-window strongly affected the mean glance duration responses (Table 3). Notably, subjects using the navigation display with a sub-window spent significantly longer looking at the display (1.74 sec) than those without a sub-window (1.05 sec), as shown in Fig. 4. This result indicates that the use of a sub-window significantly increases distraction during driving. The e-map format effect and the effect of the interaction between the e-map format and sub-window presence were insignificant in terms of mean glance duration.

3.3. Number of glances

The ANOVA results demonstrate that both e-map format and sub-window presence significantly affected the number of glances (Table 3). Fig. 5 illustrates the differences in number of glances made between the 2D and 3D displays, both with and without a sub-window. We observed a significantly greater number of glances (approximately twice as many) when subjects used a sub-window as compared to subjects without a sub-window. Further, regardless of whether a sub-window was displayed, subjects looked at the 3D display significantly more often than the 2D display. This result suggests that: (1) the presence of a sub-window makes the driver look at the display significantly more frequently; (2) the use of 3D display increases distraction in driving,
as compared to the use of 2D display.

**4. Discussion**

The section below discusses the direct results of the experiment. This section describes some important findings and recommendations regarding in-vehicle navigation system design.

**4.1. 2D versus 3D e-map**

This investigation used the same route and navigation system with either a 2D or a 3D e-map format. The analytical results show no significant difference in driving performance (error count) between 2D and 3D displays. Thus, we suggest that the 3D display is not superior to the 2D display in real road navigation tasks. This conclusion is consistent with the findings of Van Orden and Broyles (2000), as well as other studies (Tham and Wickens, 1993; Ellis, et al., 1991), which determined that for numerous tasks, performance does not differ between the use of 2D and 3D displays. This indicates that a well-designed 2D display provides adequate assistance for everyday driving. Therefore, 3D display technology may be best suited to other complex tasks, such as local air traffic control or planning and control of military operations associated with amphibious naval warfare (Van Orden and Broyles, 2000).

Our analytical results reveal that drivers look more frequently at the 3D display than the 2D display. This finding may be a result of the poor design of the 3D display used in this study. The 3D e-map covered only slightly more than half the screen, while the 2D
e-map filled the entire screen (Fig. 1). Because of foreshortening, the 3D e-map did not display the distances involved as clearly as the 2D e-map, and the decision point frequently appeared obscured in the 3D display. Additionally, the 3D e-map contained more complex colors and irrelevant background objects than did the 2D e-map. Studies have argued that a highly complex graphics are difficult to interpret quickly and correctly (Evans and Stevens, 1997). All of these factors can be considered as contributing to the greater levels of diversion of attention when using the 3D e-map format compared with the 2D e-map format.

As discussed, the comparison of the 2D and 3D displays may be confounded by the poor design of the 3D e-map in this work. In terms of driving performance, the 3D display performed as well as the 2D display. Thus, it may be premature to simply assume that the 2D e-map is entirely superior. Various methods exist for presenting 3D e-maps using different perspectives and scales. Further research is required to develop a better designed 3D display, which may be equivalent or superior to the 2D display in terms of visual demands.

4.2. **Sub-window effect**

We observed significantly fewer navigation errors as a result of the use of a sub-window (as opposed to no use of sub-windows). This result suggests that a sub-window significantly improves display legibility and interpretation by providing prominent and clear turn information as the driver approaches each decision point. Consequently, the incorporation of sub-window instructions may improve navigation system effectiveness.

Additionally, the navigation display utilizing a sub-window resulted in significantly
greater distraction (1.74 sec mean glance time; 35.57 mean number of glances) than use of a display without a sub-window (1.05 sec mean glance time; 17.93 mean number of glances). Because the participants’ attention was strongly attracted by a sub-window, they examined the navigation display more frequently and for longer periods of time. Although the use of sub-windows can improve driving performance, it adversely impacts visual demand. Thus, we believe that a trade-off remains between the two objectives of driving performance and visual demand. This statement demonstrates the need for further research to design a better sub-window that reduces the visual demand associated with looking at the navigation display.

The mean duration of glances at the display with a sub-window (1.74 sec) and without a sub-window (1.05 sec) can be considered acceptable in this work, as the subjects usually slowed when approaching an intersection. The observer noted that the car speed was between 15 and 25 km/h when approaching a decision point. However, when driving on the highway or at higher speeds, the mean glance time of 1.74 sec observed in this study is potentially dangerous. For safety reasons the voice guidance function of the navigation system should be activated during high-speed driving. Previous research has suggested that voice guidance can effectively reduce the visual demands associated with using a navigation aid.

4.3. Limitations of the study

This study presents some significant limitations that require consideration. One limitation involves the fact that the subjects examined in this study were all novice users of the navigation system. Lack of training or experience in the use of on-board
navigation equipment may be a primary cause of the errors made by subjects during the driving trials. Performance may improve dramatically after even minimal training. Thus, future studies can examine whether or not a learning effect exists and whether training or experience improves driving performance when using a navigation aid.

The small group size (n = 7) represents another limitation of the experiment. The danger of using too few subjects is that it will result in incorrect conclusions regarding an independent variable not affecting a dependent variable when, in fact, it does (Sanders and McCormick, 1993). Since the probability of Type II Errors in the present work was nearly 0.19, we have no sufficient evidence to confirm no differences in error count or mean glance duration between use of the 2D and 3D formats. Further investigation using additional subjects would be required to verify whether the e-map format affects driving performance and mean glance duration.

The findings and implications of this study are most applicable to the design of driver guidance applications. The generalization of the results to other guidance applications for different populations may be limited. For example, the newly pedestrian guidance applications should deliver more detailed information to pedestrians, referring to points of interest, such as banks, restaurants, or landmarks (Roger, et al., 2009).

5. Conclusions

This study examined how e-map format and presence of a sub-window in in-vehicle navigation displays influences driving performance and visual glance behavior in an on-road test. Our experimental results confirmed that significantly fewer navigation errors and more frequent and longer visual glances occurred when navigating a route
using a sub-window, as compared to navigation of the same route without the use of sub-windows. Notably, the number of driver navigation errors is influenced more by the presence of sub-windows than by e-map format. Since driving performance did not differ significantly between use of the 2D and 3D e-map formats, the 2D e-map may be recommended for use based on its simplicity. Further, the analytical results suggest that viewing the scene from directly overhead (2D e-map) involves less visual demands than the false perspective implicit in the 3D display. To boost driving performance, we recommend that designers improve the sub-window display by increasing the contrast between the paths and the surroundings. Simplifying the e-map representation by eliminating irrelevant information (icons or text) from the principal display would also be a useful improvement. Together, our findings provide useful information for manufacturers regarding the optimal design of an adequate navigation display, enhance users’ assessments of trust in the e-map (Seong and Bisantz, 2008), as well as how to select and adjust the format of a navigation system to better suit drivers.

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Table Captions

Table 1. Attributes of the five decision points in the experimental route.

Table 2. Means and standard deviations of the three dependent variables and their normality testing results.

Table 3. Summary of the ANOVA results for the three dependent variables. The numerical data are comprised of $p$-values.

Figure Captions

Fig. 1. Examples of four experimental conditions tested with the navigation display.

Fig. 2. Amplified map of the test route. □, starting point or destination point; ●, decision points. Numbers on the map indicate the sequence of the five decision points.

Fig. 3. Mean number of navigation errors made with or without the use of a sub-window.

Fig. 4. Mean duration of glances targeting the display made with or without the use of a sub-window.

Fig. 5. Mean number of glances towards the display for the two display types, 2D and 3D, with or without the use a sub-window.