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Glancing at Personal Navigation Devices Can Affect Driving: Experimental Results and Design Implications

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ABSTRACT
Nowadays, personal navigation devices (PNDs) that provide GPS-based directions are widespread in vehicles. These devices typically display the real-time location of the vehicle on a map and play spoken prompts when drivers need to turn. While such devices are less distracting than paper directions, their graphical display may distract users from their primary task of driving. In experiments conducted with a high fidelity driving simulator, we found that drivers using a navigation system with a graphical display indeed spent less time looking at the road compared to those using a navigation system with spoken directions only. Furthermore, glancing at the display was correlated with higher variance in driving performance measures. We discuss the implications of these findings on PND design for vehicles.

Categories and Subject Descriptors
H5.2. User Interfaces: Evaluation/methodology.

General Terms
Measurement, Design, Reliability, Experimentation, Human Factors.

Keywords
In-car navigation, user interfaces, driving performance.

1. INTRODUCTION
As computer form factors shrink and communication bandwidth and networks expand, ubiquitous computing is starting to play an increasingly important role in our lives. This prospect is particularly exciting with regards to interaction with users while they are engaged in the manual-visual task of driving. In some countries, driving is the primary mode of commuting. For example, according to the U.S. Census Bureau [1], Americans spend more than 100 hours a year commuting on the road. Given the large amount of time that some people spend behind the wheel, and the increasing availability of computational resources that can now operate inside a vehicle, many companies have been introducing a myriad of mobile services and functionalities into the consumer market just for drivers. A few notable examples are hands-free voice dialing, GPS navigation, live traffic reports, automated directory assistance, and infotainment systems. Unfortunately, the question of how these in-car services impact driving performance remains largely unanswered.

This paper addresses the effect of in-car personal navigation devices (PNDs) on driving. In order to guide drivers, a PND usually combines a map-based visual display of the GPS location of the vehicle with spoken directions. However, any visual output to the driver may constitute a potentially dangerous source of distraction. As such, we sought to answer two important research questions:

1. *Does a PND with combined visual and spoken output cause drivers to spend less time looking at the road ahead than a PND that provides spoken output only?*
2. *What is the effect of glancing at the PND visual display on driving performance?*

These two questions are motivated by an industry trend towards PNDs with increasingly sophisticated graphical user interfaces (GUI), such as 3D views of the terrain [2][3]. At the same time, many mobile phones with much smaller screens offer driving directions that rely primarily on spoken output to guide users, such as the Verizon VZ Navigator [4].

This paper is organized as follows. After surveying related research in Section 2, we describe the experiment we conducted using a high fidelity driving simulator to address the two research questions above in Section 3. We report our results in Section 4 and discuss the implications of our results on PND design in Section 5. Finally, we conclude with directions for future research.

2. RELATED RESEARCH
Although many researchers have worked on evaluating the visual and cognitive load of driving as well as that of participating in concurrent activities such as talking on a cell phone [5], no research to date has specifically explored the effects of interacting with a PND on driving performance. We now describe the most

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Figure 1. 180º field of view driving simulator.

relevant prior work that either sets a precedent for our experimental methodology or discusses similar in-car interfaces.

Because assessing driving performance in real vehicles can be impractical and hazardous, simulator studies are a common way to evaluate driving performance as well as visual attention while interacting with in-car devices. The work of Lew et al. supports the validity of this approach [6] and researchers often make design recommendations based on simulator studies. In fact, Lew et al. explored how well simulator performance could predict driving performance among participants recovering from traumatic brain injury. The authors reviewed a number of studies on this topic and found it difficult to compare results, due to a lack of standard driving simulator scenarios. In their study, they used driving performance measures from the simulator, such as lane position variance and steering wheel angle variance, in conjunction with human observation data, to predict driving performance at a future date (when participants have hopefully recovered some of their abilities lost to the injury). They found that simulator performance measures were good predictors of future driving performance in the real-world.

Besides simulator studies, a few large-scale naturalistic studies have also been conducted. In order to assist the development of crash countermeasures, Neale et al. [7] collected data about the driving habits, performance and other factors of 100 drivers over a period of one year. Their study provides useful data on the causes of crashes and near-crashes; for example, the most common causes involved a lead vehicle braking. Indeed, the unexpected events we generated in our simulator experiment were informed by their study.

While our experiment assesses the effects of PND output on driving performance, Tsimhoni et al. investigated the effects of entering addresses while driving using word-based speech recognition, character-based speech recognition and typing on a touch-screen keyboard [8]. They found that employing speech recognition allowed for shorter and safer address entry than using a keyboard.

Prior research has examined a variety of other in-car devices, and even cognitive architectures for predicting the effect of in-car interfaces on driving performance [9]. In a simulator experiment, Chisholm et al. [10] looked at manual-visual interactions with mp3 players while driving. They found that complicated interactions with the mp3 player increased reaction time to road

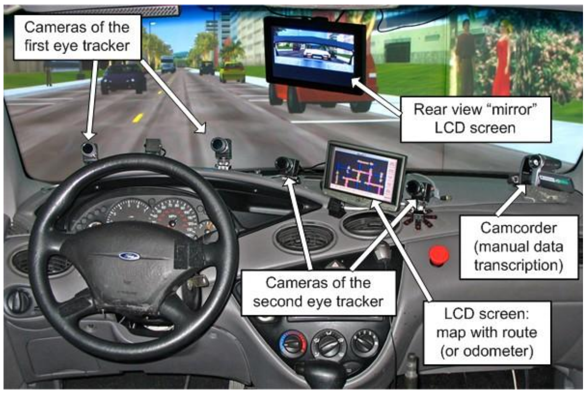


Figure 2. Experimental setup inside the vehicle.

hazards. Using an eye gaze tracker, the study also concluded that the interactions re-directed driver attention from the road to the mp3 player, increasing the chance of crashes. Medenica and Kun [11] compared the driving performance of participants when using a police radio's manual user interface versus a speech user interface. They found that using the manual user interface degraded driving performance significantly whereas using the speech interface did not.

Using a simulator experiment, Horrey et al. investigated the influence of in-car devices in general on the visual attention of drivers and driving performance [12]. They found that as the amount of time drivers spent observing the outside world (or the percent dwell time on the outside world) decreased, the variability in lane position increased. In other words, their experiments showed that visual distractions negatively influenced driving performance. While general findings provide critically important guidance, they need to be validated for specific domains. Our simulator experiment validates their finding specifically for PNDs.

3. EXPERIMENT

Before we delve into the details of our simulator experiment, it is worth noting that we conducted a preliminary study comparing paper directions against a PND with and without a visual display [13]. In examining the ways in which a PND in general was better than paper directions, and observing how drivers with a visual display spent less time looking at the road than those with spoken directions only, we decided to conduct a follow-up experiment that could more thoroughly inspect the relationship between glancing and driving performance. We did this by making the simulation more typical of a city route, with short and long road segments, ambient traffic conditions characteristic of city driving, and pedestrians walking here and there. In other words, we developed a more "realistic" simulation populated with things to look at – primarily, other cars and people. We now describe how we conducted the simulator experiment and collected data.

3.1 Equipment

Our experiment was conducted in a high-fidelity driving simulator with a 180º field of view. As shown in Figure 1, the simulator provides a full-width automobile cab on top of a motion base that allows drivers to feel bumps in the road as well as braking. Figure 2 displays the equipment inside the vehicle. Because we were interested in visual attention, we equipped the simulator with two eye trackers that provide gaze information from two cameras

Figure 3. LCD screen displaying real-time location of the vehicle on a map.

each. Figure 2 also shows where we mounted a 7'' LCD screen for displaying map information. PNDs are typically mounted either on the windshield, on top of the dashboard, or are built into the dashboard. We decided to place the LCD screen on top of the dashboard because the gaze angle generally has to change less if the PND is located higher than if the PND is built into the dashboard. Although a 7'' screen is typically larger than most portable PNDs, our larger screen ensures that users can clearly see the map and read the street names. Indeed, the consumer market has exhibited a steady trend toward larger screen PNDs with greater multimedia functionality.

3.2 Method

3.2.1 Participants

We collected data from 8 male participants. All were university students between the ages of 21 to 29 (the average age was 22.4). They received a $15 gift card to a popular store chain for their participation.

3.2.2 Procedure

Participants in the experiment interacted with two types of navigation aids:

1. Standard PND directions: Standard PNDs provide real-time map location as well as turn-by-turn spoken directions. Likewise, our LCD screen presented users with real-time location of the vehicle in the simulator world along with spoken prompts for impending turns. Figure 3 shows the LCD screen with map information. The map was presented in a dynamic, exocentric, forward-up view, where the car remains at the center of the screen while the road moves. In order to eliminate problems associated with the comprehension of synthesized speech while driving [14], we used spoken prompts recorded by a female voice talent.

2. Spoken directions only: Here, we utilized the same spoken prompts as in the standard PND and displayed no map information on the LCD. The spoken directions provided distances to the next turn (e.g., "In 75 yards turn right onto Fifth Avenue."). Because the simulator does not provide an odometer, we displayed odometer information on the LCD.

The experimental protocol proceeded as follows. Participants were given an overview of the simulator and the driving and navigation tasks, and were then trained in the driving simulator.

Figure 4. Simulated two-lane city road with lane markings and ambient traffic. The image also illustrates an unexpected event: a pedestrian walking into the roadway from behind a vehicle parked on the side of the road.

Training consisted of driving in a city environment as shown in Figure 4. Participants were instructed to drive as they normally would and to obey all traffic laws. They first drove for about 5 minutes following directions from a standard PND and then another 5 minutes following directions from a PND with spoken directions only. During training, participants were exposed to two unexpected events, one for each navigation aid. In one event, a pedestrian walked out from behind a vehicle parked on the side of the road (see Figure 4), and in the other, a parked vehicle pulled out and cut off the participant. Participants were warned that they may encounter such events before they started the driving portion of their training.

After training, participants completed two routes, one for each of the navigation aids. Two routes were used to prevent participants from learning the directions over the course of the experiment. In order to keep the driving task complexity equal across routes, the two routes were identical, and participants simply traversed them in different directions for the two PNDs. Figure 5 displays the route used in the experiments (bottom left side). Roads were presented in daylight with ambient traffic characteristic of city driving. Each route consisted of two-lane (one lane in each direction) city roads, with lane markings, all with 3.6 m wide lanes. The total route lengths were 10 km and each took about 15 minutes to complete. Each route also exposed participants to three unexpected events, as listed in the legend of Figure 5.

In this paper, we concentrate on two-lane city roads with lane markings, ambient vehicle traffic and pedestrian traffic (e.g., Figure 4). We focus on these roads because this type of road demands constant visual attention from drivers. This, in turn, means that driving performance measures and visual attention are likely to be affected by differences in the visual demands of the two navigation aids.

3.2.3 Design

We conducted a within-subjects factorial design experiment with the two navigation aids as our primary independent variable, *Nav*. The order of *Nav* was counter-balanced among the participants. We measured the following dependent variables.

Standard driving performance measures. We recorded the variances of lane position, steering wheel angle and velocity. In

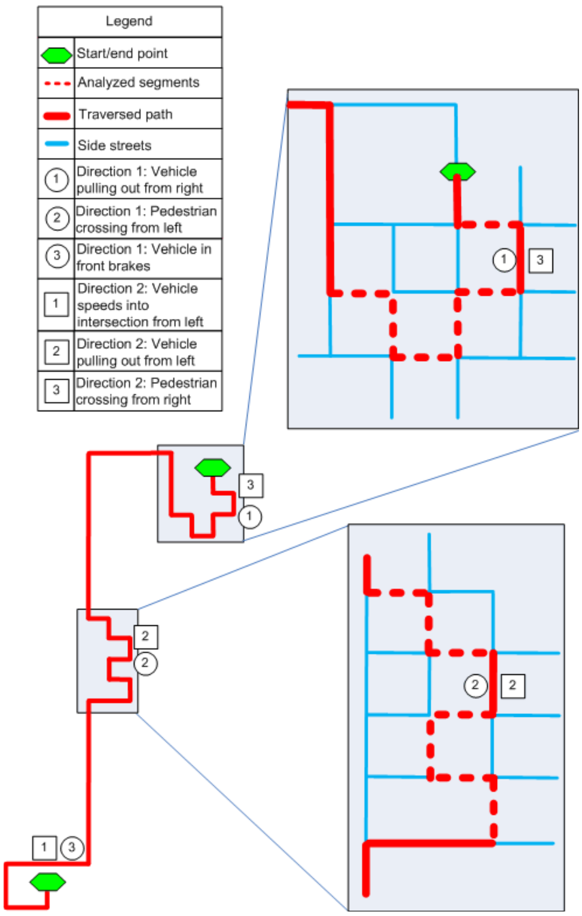


Figure 5. The simulated route (bottom left) and the short segments (right) used for analysis. Use the legend to locate the traversed path, the analyzed short segments, and the location of unexpected events.

each case, a higher variance represents worse driving performance. We also analyzed the mean velocity of travel for each participant. A lower mean velocity may indicate harder perceived driving conditions.

Lane position constitutes the position of the center of the simulated car and is measured in meters. Clearly, large variances in lane position are the most serious sign of poor driving performance, since they indicate that the participant has weaved in his/her lane, and perhaps even departed from the lane.

Steering wheel angle is measured in degrees. In the case of curvy roads, large steering wheel angle variance is not in itself a sign of poor driving performance. After all, just following a curvy road requires varying the steering wheel angle constantly. However, steering wheel angle variance can be used as a relative measure of driving performance when comparing the performance of multiple participants on road segments of similar driving difficulty. A higher variance is an indication of increased effort expended by a driver to remain in his/her lane.

The *velocity* of the vehicle is measured in meters/second. A relatively large variance in the velocity of a car does not necessarily indicate unsafe driving. However, drivers often reduce speed when they are concerned about safety or when they are distracted. For example, a driver may slow down on a narrow road or when talking to a passenger. Similarly a low mean velocity for a portion of the road may indicate that the driver was concerned about safety or otherwise distracted.

Number of collisions. We counted the number of instances when the participant's vehicle touched another object, such as a parked or moving vehicle, a pedestrian, etc. Based on our experience with simulator studies, we did not expect collisions to happen during normal driving, but thought they might occur when drivers were confronted with unexpected events. Since the unexpected events were designed to be avoidable by an alert driver, any collision during such an event may indicate distraction.

Percent dwell time (PDT) on the outside world. The *PDT* is the percentage of time that the participant spent looking at items displayed on the three simulator screens (most importantly the roadway). A low value may indicate that the driver was distracted, which in turn could lead to collisions. In addition to total PDT, we also tracked changes in PTD as participants traveled between intersections. Changes in PDT that depend on proximity to a given intersection may shed light on what causes distractions and hopefully lead to better PND designs that can avoid these dips.

Cross-correlation peaks. We performed cross-correlation analyses to identify time lags in increased variance for lane position and steering wheel angle (if any) in response to decreased PDT on the outside world. Peaks in the cross-correlation of the PDT on the outside world and the variance of a driving performance measure may indicate a causal relationship between decreased PDT and increased variance. If a peak exists for a given lag between the PDT and the variance of a driving performance measure, the lag (expressed in seconds) may indicate the time lag between the onset of decreased PDT on the outside world (e.g. due to a participant looking at the standard PND) and the increase in the variance of the driving performance measure.

3.2.4 Measurement

Raw data for the four driving performance measures were provided by the simulator and sampled at a 10 Hz rate. Using the eye tracker, we also recorded gaze angles throughout the experiment. Eye tracker data was sampled at a 60 Hz rate. Using the eye tracker, we automatically classified gazes as being directed at the outside world if the participant was looking at any of the simulator's front projection screens.

For the rare cases in which the eye tracker could not track a participant's gaze (e.g. when the participant's hand blocked the eye tracker's view of his/her eyes for an instant), we reviewed video footage obtained from the eye tracker cameras as well as from the camcorder in the simulator (Figure 2) and hand-transcribed dwell times.

3.2.5 Calculation

As discussed in section 3.2.2, our experiment presented participants with city driving routes. The routes can be broken up into segments by treating roads between two intersections as separate segments. Figure 5 displays the route used in the experiments (bottom left side) and zooms in on the short segments of the routes used in the experiment (right). We calculated all of our results, such as the variances and mean velocity, using data from 13 segments. These segments all had the same characteristics, thereby controlling factors that could potentially confound our results. In particular, the segments were short, with 200 meters separating the centers of adjacent intersections. Although longer segments were utilized in the routes to make the driving task feel more realistic, we expected that participant driving patterns (e.g. the frequency content of the vehicle velocity reflecting the acceleration and deceleration over a segment) and visual attention patterns (how often and where people look) would be different for segments of different lengths, making comparisons between them difficult.

Furthermore, at both the beginning and end of each segment, there was a four-way intersection where participants made either a right or left turn. Although routes had short (200 m) segments that did not meet this criterion (e.g. when participants entered some of the short segments by driving straight through a four-way intersection), we did not include them. Driving performance and visual attention are likely to be different on these segments than on segments where one or both of the turns may be missing.

Finally, participants did not encounter an unexpected event in the segments we analyzed. Unexpected events may require sudden braking and steering wheel motion, which in turn can result in very large variances for these measures, again making comparisons with other segments difficult.

In analyzing all of the segments, we excluded data collected close to the intersections. This was done because driving performance data at the beginning of a segment is typically dominated by the turning maneuver that is necessary to get through the intersection, and data collected at the end of a segment is dominated by deceleration before turning. Variances resulting from the effects of turning maneuvers and deceleration close to intersections are much larger than variances encountered in data generated away from the intersection, which of course makes it difficult to compare intersection and straight segment data. In particular, we excluded data generated 60 meters after exiting the previous intersection and 40 meters before an upcoming intersection, and analyzed data generated over (200 – 60 – 40) m = 100 meters.

3.2.5.1 *Driving Performance*

For each participant and navigation type, the variances of the driving performance measures (lane position, steering wheel angle and velocity) were calculated for each short segment. The same was done for average velocity. We then calculated the average of the variances and velocities for the segments.

We also searched the simulator log files for signs of collisions between the simulated vehicle and surrounding objects.

3.2.5.2 *Visual Attention*

For each participant p and navigation aid *nav*, we also calculated the average percent dwell time, $APDT_{p,nav}$, on the outside world by finding the ratio of the sum of dwell times for all 13 segments and the sum of the total time spent traversing all 13 segments. We used the same approach in calculating the APDT at the standard PND for parts of the experiment when this PND was in use. Finally, we used an analogous approach to calculate how the APDT at the road ahead changed as participant vehicles traveled through five 20 meter segments between consecutive intersections (from 60 m after the preceding intersection to 40 m before the upcoming intersection).

3.2.5.3 *Cross-correlation*

We calculated the cross-correlation between the instantaneous percent dwell time, IPDT, on the outside world and the short-term variance of two driving performance measures: lane position and steering wheel angle. The IPDT was calculated at a 10 Hz rate by calculating a separate PDT for each consecutive 100 ms window of eye tracker data. Since the eye tracker data is recorded at 60 Hz, we calculated instantaneous PDTs using six eye tracker data samples at a time. For cross-correlation calculations, the IPDT was transformed into the transformed IPDT (TIPDT) such that a TIPDT value of 0 represented 100% IPDT (attention fully on the outside world), while a TIPDT value of 1 represented 0% IPDT (e.g. when the participant is looking at the LCD screen). Thus peaks in the cross-correlation indicate worse driving performance (larger variance values) correlated with reduced visual attention on the outside world (larger transformed IPDT values).

The short-term lane position and steering wheel angle variances, were calculated at a 10 Hz rate for 1 second long windows (i.e., for 10 samples of the given driving performance measure at a time). The choice of 1 second for the window length reflects our expectation that on straight roads the corrections to lane position, accomplished by relatively large changes in the steering wheel angle, will take less than 1 second.

We calculated two cross-correlations. $Rlp_{nav}[lag]$ is the cross-correlation between lane position variance and the TIPDT on the outside world for navigation aid *nav*. Rlp_{nav} was calculated as the average of cross-correlations for each of the 13 segments and each of the 8 participants. $Rstw_{nav}[lag]$ is the cross-correlation between the steering wheel angle variance and the TIPDT and it was calculated analogously to $Rlp_{nav}[lag]$. Both calculations were implemented using Matlab's xcorr function. The *lag* variable indicates the number of samples by which the variance measure lags behind the PDT measure. Thus, for positive values of lag, a peak in the cross-correlation indicates that there is an increase in the variance following an increase in the time the participant spent not looking at the outside world.

3.3 Results

3.3.1 *Driving Performance*

We performed a one-way ANOVA for each of the driving performance measures with *nav* as the independent variable. We found no significant effects for any of the three variances of driving performance measures or for average velocity. This result mirrors our findings in our preliminary study [13]. We also found no collisions in any of the experiments. Hence, participants were able to pay sufficient attention to the road to avoid contact with other objects or pedestrians.

3.3.2 *Visual Attention*

To assess the effect of different navigation aids on visual attention, we performed a one-way ANOVA using PTD as the dependent variable. As expected, the time spent looking at the outside world was significantly higher when using spoken directions as compared to the standard PND directions, $p<.01$. Specifically, for spoken directions only, the average PDT was 96.9%, while it was 90.4% for the standard PND.

To assess the effect of distance from the previous intersection on PDT on the outside world for the two navigation aids, we performed one-way ANOVAs for each of the navigation aids using PDT as the dependent variable. For the standard PND, we found a significant main effect, $p<.01$, while the effect was less significant for the PND with spoken output only, $p<.05$. Figure 6 shows the differences in PDT on the outside world. For the standard PND, we also assessed how the PDT on the PND screen changes with the distance from the previous intersection. Using a

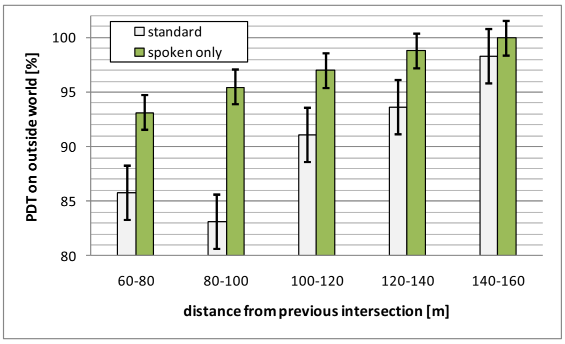


Figure 6. PDT on the outside world (with standard error), changing as vehicles travel between intersections.

one-way ANOVA we again found a significant main effect, $p<.01$. Figure 7 shows the differences in PDT on the LCD screen for the standard PND. These results indicate that on short road segments, when drivers are expecting to possibly turn at the upcoming intersection, they are likely to look at the display of a standard PND. However, they are less likely to do so as they approach the next intersection.

3.3.3 Cross-correlation

Our cross-correlation analysis indicates that there is a relationship between the IPDT on the outside world and the two short-term variances. This relationship is evident from peaks in the two cross-correlation functions, $Rlp_{nav}[lag]$ and $Rstw_{nav}[lag]$, shown in Figure 8. In order to evaluate whether the peaks arose due to chance, we conducted a randomization test in a manner similar to the one used by Veit et al. [15]. Specifically, while we used pairs of sequences of TIPDT and variance values from the same segment in our cross-correlation calculations (section 3.2.5.3), in our randomization test, we found the cross-correlation between the TIPDT from one segment and variances from a different segment. We created 1000 random arrangements of TIPDT values with respect to the variances. Thus, for each value of *lag* we had 1000 cross-correlation results. For each value of *lag* we then found the bottom $(1-p)\cdot 1000$ cross-correlation values. We estimated statistical significance by comparing cross-correlation values for the original data with these values. If the cross-correlation for the original data was larger, then the result was considered statistically significant with probability less than p. E.g. to estimate the $p<.05$ significance level, we found the bottom 1000 - 50 = 950 cross-correlation values for each value of *lag*. If, for a given value of *lag*, the cross-correlation value from the original data was larger than these values, the result was statistically significant with $p<.05$.

The cross-correlation results are shown in Figure 8. As the graph in the top part of Figure 8 indicates, for the standard PND, the cross-correlation between transformed instantaneous PDT on the outside world and short-term lane position variance, $R_{lp,standard}$, has several statistically significant peaks. For the most prominent of these peaks, the lag is about 0.8 seconds, indicating that an increase in the lane position variance follows reduced attention to the outside world. The graph at the bottom of Figure 8 indicates that similar peaks exist for the steering wheel angle variance ($R_{stw,standard}$). The two graphs also show that statistically significant peaks exist for PND with spoken directions as well. In tracing the source of the peaks, we found that when drivers were not looking at the roadway, they were looking at either the speedometer,

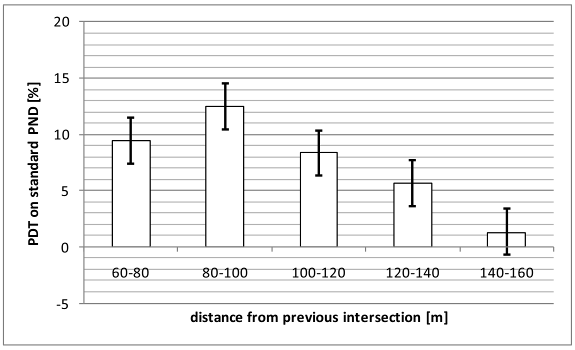
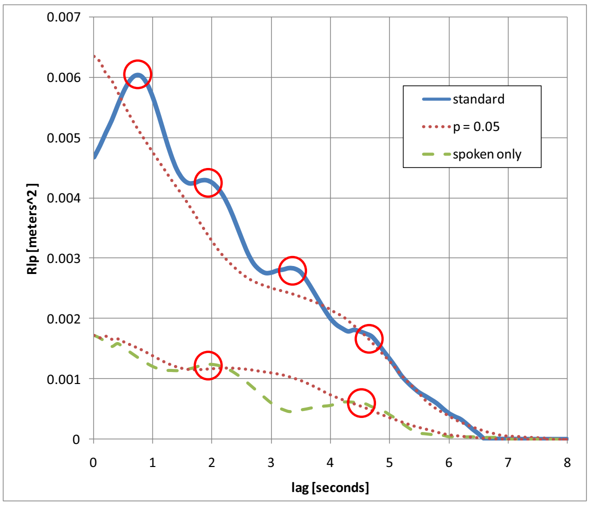


Figure 7. PDT on LCD screen of the standard PND (with standard error), changing as vehicles travel between intersections.



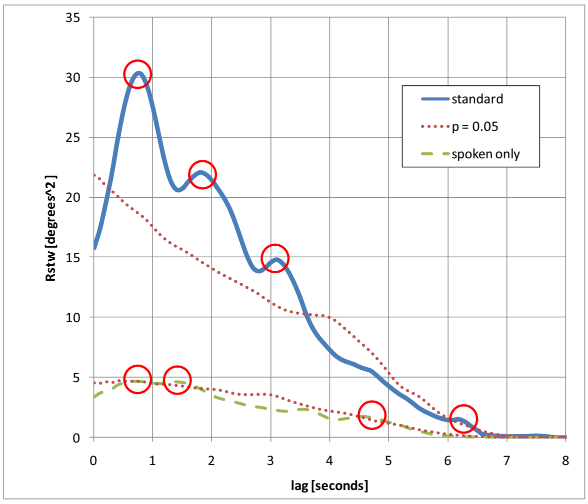
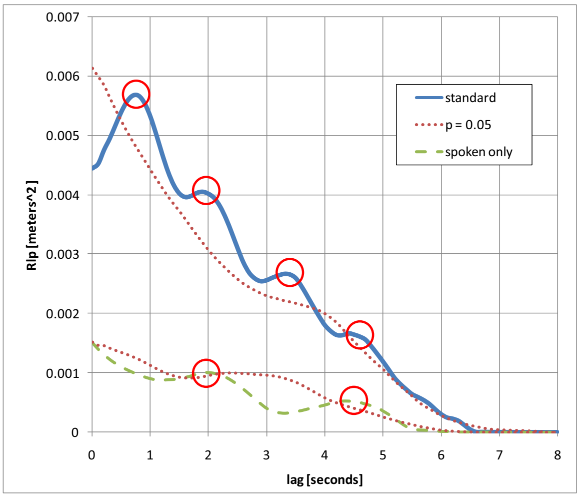


Figure 8. Cross-correlation between TIPDT on the outside world and lane position variance (top) and steering wheel variance (bottom). Circled peaks indicate statistically significant increases in variance occurring after decreases in the IPDT, with the delay indicated by the value of lag.

dashboard, or steering wheel. This is to be expected. However, the peaks for the spoken directions are about six times smaller than for the standard PND.

Why is there such a difference in the magnitude of the effects? Our data indicates that the answer is in the length of gazes drivers use to view the standard PND. Figure 9 again shows cross-correlation values for the two navigation aids, however in this case the cross-correlations were calculated using gazes away from the outside world that are 200 ms or more in length. Clearly, there is a striking resemblance between the graphs in Figure 8 and Figure 9, respectively: peaks are located in practically the same locations and the magnitudes are almost the same. We can conclude that gazes away from the outside world lasting 200 ms or longer are the major contributors to peaks in the cross-correlations. And, as Figure 10 shows, about 60% of all fixations (gazes at the same location lasting at least 100 ms) at the standard PND are in fact at least 200 ms long.



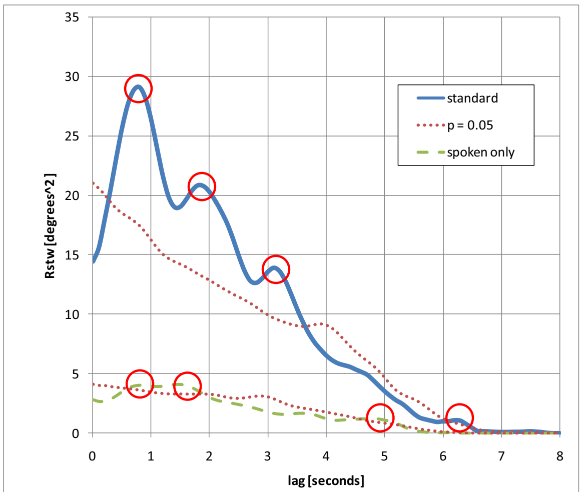


Figure 9. Cross-correlation between transformed instantaneous PDT on the outside world and lane position variance (top) and steering wheel variance (bottom). Calculated only using gazes away from the outside world of 200 ms or longer. Circled peaks indicate statistically significant increases in variance occurring after decreases in the IPDT, with the delay indicated by the value of lag.

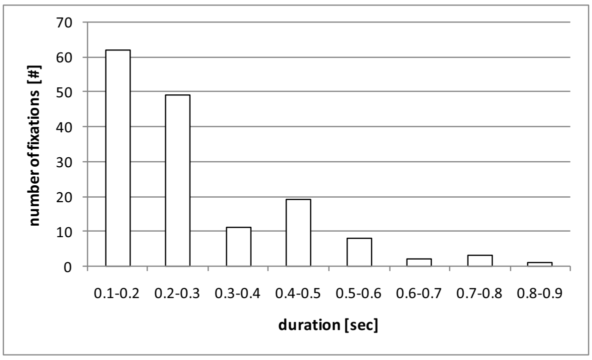


Figure 10. Fixations at the standard PND by duration.

In summary, whenever drivers look away from the road in such a way that it causes higher variance in lane position or steering wheel angle, it is because they are spending at least 200 ms doing so. When a visual display is present, the magnitude of the effect on driving performance is about six times greater. This is probably due to the fact that unlike looking at the dashboard, looking at a map that is changing in real-time requires a fair amount of cognitive effort. Drivers need to mentally parse the information in the display, and that is more distracting.

4. DISCUSSION

In our introduction, we started out by asking two questions.

1. *Does a PND with combined visual and spoken output cause drivers to spend less time looking at the road ahead than a PND that provides spoken output only?*

Because we found a significant difference in visual attention directed at the outside world for the two navigation aids, with drivers spending less time looking at the road ahead when they had a visual display, the answer to this question is affirmative. Note that glancing at the visual display was not necessary to complete the navigation task. In fact, there were no cases of missed directions for any of the navigation aids. For the city route and traffic conditions utilized, spoken directions provided sufficient information without introducing a visual distraction.

2. *What is the effect of glancing at the PND visual display on driving performance?*

Despite the fact that we did not find significant differences in driving performance measures when averaging over all segments, we did find statistically significant peaks in the cross-correlation between the TIPDT on the outside world and the short-term lane position and steering wheel variances. These peaks indicate that there may be a causal relationship between looking away from the outside world (e.g. to look at the PND), and an increase in the variance of lane position and steering wheel angle. We also found that the cross-correlation peaks are larger for gazes away from the outside world lasting 200 ms or longer. This is important since about 60% of all fixations at the standard PND were at least 200 ms long. In other words, the way in which users interact with standard PNDs very often results in looking away from the outside world for more than 200ms at a time. This in turn is correlated with increased short-term lane position and steering wheel variances. Although any increase in the risk of accidents due to these increased variances still needs to be quantified, our results provide designers of in-car navigation aids with reason for caution and a framework for assessing any negative impact on driving due to visual displays.

4.1 Design Implications

With respect to designing in-car navigation aids, our results seem to suggest that if users can trust a PND enough to follow whatever spoken directions they are given, even when they are lost, a navigation system with no visual display may be the most favorable option since visual attention and consequently driving performance will likely be improved. This finding is important for two reasons. First, any sophistical GUI that could hold a driver's attention even more than the simple 2D view we presented, such as 3D terrain maps [2][3], is likely to affect driving performance in an even worse way. Second, small PND devices that rely primarily on speech present viable alternatives to the typical GPS form factor. For example, Verizon VZ Navigator [4] provides spoken turn-by-turn directions along with a map, but on some phones (e.g., flip phones), the map and text are too small to read. Our research suggests that, if the map is intentionally turned off, using these devices may not result in worse driving performance than using PNDs with larger displays, and may even result in better visual attention and consequently better driving performance.

The key to a successful PND interface may be to earn the trust of the users. At the end of our experiment, we asked participants to rate their experiences with the three navigational aids. Five of the eight participants strongly agreed or agreed with the following statement: "I prefer to have a GPS screen for navigation." We hypothesize that this sentiment will be especially strong on roads where users may seek reassurance that they are on the right path. For example, on long road segments, drivers may get anxious that they have missed a turn and may want to get feedback from the navigation aid. These may be times when drivers cast a glance at the visual output of a navigation aid.

5. Conclusion & Future Directions

In this paper, we describe the experimental evaluation of the influence of two navigation aid types on driving performance and visual attention while driving a simulated car in a city environment. We found that participants spent significantly more time looking at the outside world when using a spoken output-only PND compared to using a standard PND with an LCD screen and spoken output. In fact, participants on average spent about 6.5% more time looking at the road ahead when using the spoken output-only PND – a difference of about 4 seconds for every minute of driving. We also found evidence that this difference negatively impacted two driving performance measures: lane position variance and steering wheel angle variance. Specifically, we found statistically significant cross-correlation peaks between the increases in these variances and decreases in the time spent looking at the outside world.

In our next investigation we intend to explore a larger variety of PND displays. We plan to explore interactions with displays that provide egocentric maps, as such maps have been shown to improve user performance on navigation tasks [16], as well as augmented reality navigation aids. We are also exploring building predictive models of when users are likely to look at the PND display for reassurance. Such models could assist the development of spoken only navigation aids that deliver prompts reassuring drivers that they are on the right track.

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