

The Effect of In-Car Navigation Aids on Driving Performance and Visual Attention

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ABSTRACT

Nowadays, personal navigation devices (PNDs) that provide GPS-based directions are common 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 appear to be less distracting than paper directions, in-car displays may distract drivers from their primary task of driving. In experiments conducted with a high fidelity driving simulator, we found that using paper directions degrades driving performance and visual attention significantly more than using a navigation device that provides either a map with spoken prompts or has spoken prompts only. This was expected. However, we also found that having just spoken prompts affected visual attention the least. 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 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, toll-free directory assistance, infotainment systems, etc. Unfortunately, the question of how these in-car services impact driving performance remains largely unanswered.

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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 prompts. However, any visual or spoken interaction with 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 affect drivers' ability to maintain driving performance differently than a PND that provides spoken output only?

2. 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?

If the answer to either of these questions is affirmative, then the visual display may be interfering with the safe operation of vehicles.

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



Figure 1. 180° field of view driving simulator.

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 [2], no research to date has compared the effects of different navigation aids on driving performance.

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 [3] 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 PNDs, a variety of in-car devices have been the subjects of investigation. In a driving simulator experiment, Chisholm et al. [4] looked at manual-visual interactions with mp3 players while driving. They found that complicated interactions with the mp3 player increased reaction time to road hazards. Using an eye gaze tracker, the study also concluded that the interactions redirected driver attention from the road to the mp3 player, increasing the chance of crashes. Medenica and Kun [5] 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.

Horrey et al. investigated the influence of in-car devices in general on the visual attention of drivers and driving performance [6]. They found that as the amount of time drivers spent observing the outside world (the percent dwell time on the outside world) decreased, the variability in lane position increased. In other

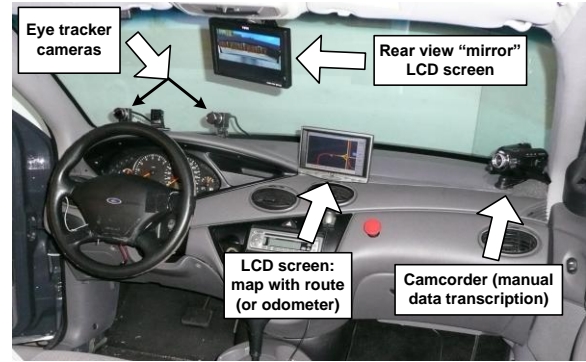


Figure 2. Experimental setup inside the vehicle.

words, their experiments showed that visual distractions negatively influenced driving performance.

While this paper addresses the effects of PND output on driving performance, Tsimhoni et al. have investigated the effects of entering addresses while driving using word-based speech recognition, character-based speech recognition and typing on a touch-screen keyboard [7]. They found that employing speech recognition allowed for shorter and safer address entry than using a keyboard.

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. [8] 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.

Apart from the above studies, researchers have explored a cognitive architecture for predicting the effect of automotive interfaces on driving performance [9].

3. EXPERIMENT

In order to assess how different in-car navigation aids influence driving performance, we conducted a controlled experiment in a high-fidelity driving simulator with a 180° 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 an eye tracker that provides gaze information from two cameras. 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. There has also been a steady trend recently in the consumer market to sell larger screen PNDs with greater multimedia functionality.

Within this simulator environment, participants interacted with three types of navigation aids:



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

1. *Paper directions:* Paper directions serve as our baseline. Despite the prevalence of PNDs, many consumers still use paper directions. In our study, participants received printed directions similar to those generated by web services such as Google Maps [10], Live Search Maps [11] and Yahoo! Local [12] on one double-sided sheet of paper. One side of the sheet provided a map of the route to be traversed. The other side provided turn-by-turn directions.

2. *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 is 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 [13], we used spoken prompts recorded by a female voice talent.

3. *Spoken directions only:* In order to examine whether the visual display of standard PND directions negatively influences driving performance, and causes participants to spend less time scanning the road ahead, as a third navigation aid, we considered the standard PND directions without the map. As such, 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, in the case of voice-only directions, we displayed odometer information on the LCD.

3.1 Method

3.1.1 Participants

The participants were 12 university students between the ages of 19 to 31 (the average age was 24). They either received free software or a gift card to a popular store chain for their participation. All participants were males who had drivers' licenses. One participant realized after working with the PND that provided spoken directions only that he did not need to look at the display of the standard PND. Consequently we rejected all of the data collected from this participant and were left with data for 11 participants.



Figure 4. Simulated two-lane city road with lane markings and light ambient traffic.

3.1.2 Procedure

Participants were given an overview of the simulator, and were trained in the driving task. Training consisted of approximately five minutes of driving along a highway and five minutes of driving in a city environment. Participants were instructed to drive as they normally would and to obey all traffic laws. After training they completed three routes, one for each of the navigation aids. This was done 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 three routes consisted of roughly the same number and type of road segments. All routes presented roads in daylight, populated by light ambient traffic. Each route consisted of multiple road types, all with 3.6 m wide lanes. The road types we used were:

- Two-lane (one in each direction) neighborhood roads with no lane markings,
- Two-lane city roads with lane markings,
- Four-lane city roads with lane markings,
- Four-lane highways with dividing barrier, and
- Six-lane highways with grassy median, as well as on- and off-ramps.

The primary differences between the routes involved reversing the direction of a path, mirroring the layout of some road segments, and guiding participants along different streets.

In this paper, we concentrate on the two-lane city road with lane markings, as shown in Figure 4, 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 three navigation aids.

3.1.3 Design

We conducted a within-subjects factorial design experiment with the three navigation aids as our primary independent variable, *Nav*. The order of *Nav* was counter-balanced among the subjects. We had five dependent variables. First, we recorded the variances of three measures of driving performance: lane position, steering wheel angle and the velocity of participants' cars. In each case, a higher variance represents worse driving performance. We also

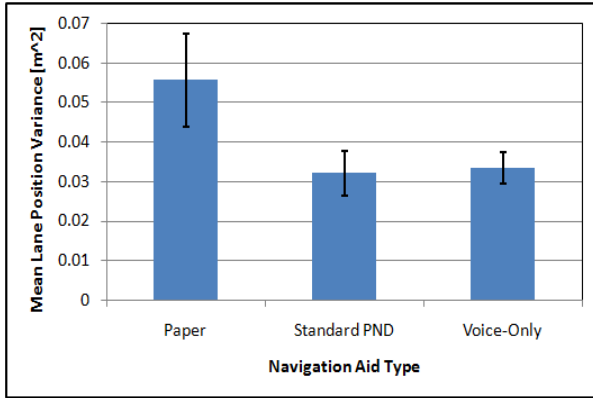


Figure 6. Mean lane position variance.

$$PDT_{p,nav} = \frac{\sum_{i=1}^{N_{p,nav}} DT_{i,p,nav}}{\sum_{i=1}^{N_{p,nav}} ST_{i,p,nav}}$$

$$1 \leq p \leq 11$$

$$nav \in \{paper, voice - and - map, voice - only\}$$

$$1 \leq i \leq N_{p,nav}$$

Equation 2. Percent dwell time for participant p and navigation aid nav .

3.2 Results

3.2.1 Driving Performance

We performed a one-way ANOVA for each of the driving performance measures with nav as the independent variable. We found main effects for lane position variance ($F(2,20)=4.94$, $p<.05$), as well as steering wheel angle variance ($F(2,20)=4.67$, $p<.05$), but not velocity variance or the mean velocity.

The mean lane position variance is shown in Figure 6. Using the paper navigation aid resulted in higher variance, which indicates worse driving performance. Indeed, post-hoc, pairwise comparisons revealed that using paper directions led to higher lane position variance than using either the standard PND directions ($p<.05$) or the spoken directions only ($p<.05$). Hence,

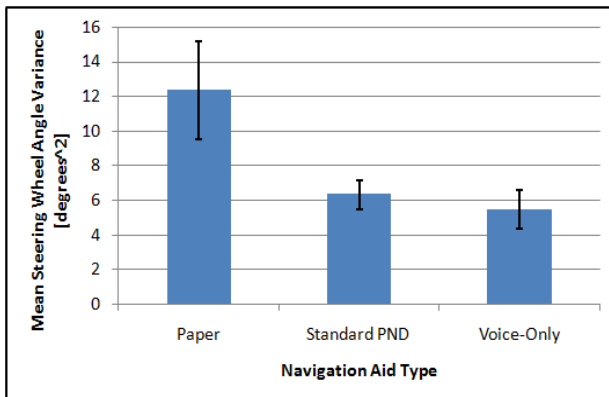


Figure 7. Mean steering wheel angle variance.

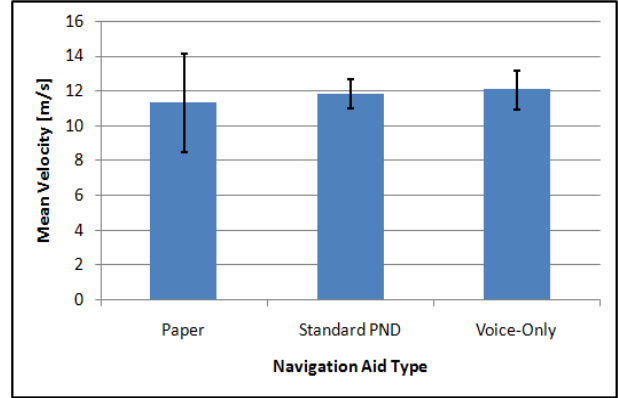


Figure 8. Mean velocity.

when paper directions were used, participants were not able to control the lane position of the car with the same degree of accuracy as with the other navigation aids. Interestingly, using the standard PND directions did not result in statistically different lane position variance than using the spoken directions only.

The mean steering wheel angle variance is shown in Figure 7. Again, using the paper navigation aid resulted in higher variance, which indicates worse driving performance. However, post-hoc, pairwise comparisons revealed that using paper directions led to higher steering wheel angle variance than using the PND with voice-only directions ($p<.05$) but not the standard PND. Hence, when paper directions were used, participants expended significantly more effort on steering than when they used the voice-only PND directions.

With respect to mean velocity, a post-hoc, pairwise comparison showed that mean velocity, as shown in Figure 8, is significantly higher when using spoken directions only than when using the paper directions ($p<.05$). This indicates that participants may have felt more comfortable with just spoken directions, presumably because they did not have to take their eyes off the road while driving, as we will examine in the next section.

3.2.2 Visual Attention

To assess the effect of different navigation aids on visual attention, we performed a one-way ANOVA using percent dwell time as the dependent variable and found a significant main effect ($F(2,20)=14.03$, $p<.001$). Figure 9 shows the differences in percent dwell time. As expected, participants looked at the road

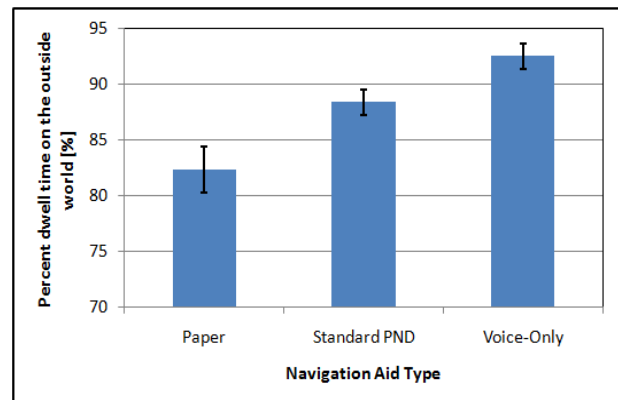


Figure 9. Percent dwell time on the outside world.

ahead the least when using paper directions and the most when using spoken directions only. Post-hoc comparisons revealed that the time spent looking at the road is significantly higher when using spoken directions as compared to the standard PND directions ($p < .05$). Similarly, time spent looking at the road ahead is significantly higher when using the standard PND than paper directions ($p < .05$).

4. DISCUSSION

As expected, using paper directions was the worst navigation aid type in terms of driving performance measures and visual attention. However, in comparing standard PND directions against spoken directions only, the picture is less clear. In the Introduction, we set out by asking two questions. The first one was:

1. *Does a PND with combined visual and spoken output affect drivers' ability to maintain driving performance differently than a PND that provides spoken output only?*

Our results did not show any significant differences in driving performance measures between the two navigation aids. However, the fact that we did not find any significant differences does not mean that there is none – merely that, with our simple driving task, the null hypothesis that the driving performance when using standard PND directions is the same as that when using spoken directions only could not be rejected. We emphasize this because of the answer to our second question:

2. *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?*

Despite the fact that we did not find significant differences in driving performance measures, we did find a significant difference in visual attention directed at the outside world for the two navigation aids. This is due to the fact that drivers would cast glances at the LCD screen while driving even when these glances were not necessary in order to complete the navigation task: in the city environment there were no cases of missed directions for any of the navigation aids (there were a small number of cases for neighborhood roads). For the city environment we used and the light traffic conditions, spoken directions provided sufficient information without introducing a visual distraction.

In light of the visual attention results, it is reasonable to return to question 1 and ask why the PND with the combined visual and spoken output did not affect driving performance differently than the PND with the spoken-only output. More to the point, how is it possible that using a standard PND did not result in worse driving performance than using a PND with spoken directions only, despite the fact that participants looked at the road ahead less with the standard PND than with spoken directions? One would expect that higher percent dwell time on the outside world would be highly associated with better driving performance measures. That expectation is probably true since good driving performance should depend on looking at the road. However, in the simulator study we conducted, the city segments were relatively short (200 to 600 m), and they included only light ambient traffic. There were no pedestrians crossing streets, no unpredictable drivers to follow, etc. This made the driving task relatively easy and drivers could maintain driving performance at a high level even while periodically looking away from the road ahead. It is likely that when we introduce more sudden driving hazards such as pedestrians, we will see better driving performance and handling

of the situation with greater dwell time looking at the road. This however needs to be experimentally verified.

With respect to the implications of our research on the design of PNDs, we need to be cautious about drawing conclusions given that we have not yet fully explored the disadvantages of using spoken directions only. However, our results seem to suggest that if users can trust a PND enough to follow whatever directions they are given, even when they are lost, using a PND with no visual display may allow for driving performance that is just as good as driving performance when using a PND with a visual display. In fact, our results even suggest that visual attention will be improved when using a PND without a visual display. This latter finding is important as PNDs come in many form factors, including mobile phones. For example, Verizon VZ Navigator [14] 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.

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. Nine of the eleven 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 three navigation aid types on driving performance and visual attention while driving a simulated car in a city environment. We found that the standard PND directions with and without a visual display of map information improved driving performance over paper directions. However, the time participants spent looking at the road ahead was significantly higher when the PND directions used spoken output only than when a visual display was involved. In fact participants on average spent around 92% of their time looking at the road ahead with spoken directions only and around 88% when using the standard PND directions – a difference of about 4%, or about 2.5 seconds for every minute of driving.

In terms of future directions, as discussed previously, we plan to conduct a follow-up study comparing standard PND directions against spoken directions in more complicated simulation environments involving complex paths (e.g., those with a quick succession of turns or ambiguous forks in the road) as well as sudden driving hazards (e.g., pedestrians). In doing so, we hope to better understand the advantages and disadvantages of navigation aids that provide mostly spoken directions. We also intend to include a larger variety of PND displays in our investigation. Specifically, we will explore interactions with displays that provide egocentric maps, as such maps have been shown to improve user performance on navigation tasks [15].

Finally, we are 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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