Simulated Augmented Reality Windshield Display as a Cognitive Mapping Aid for Elder Driver Navigation

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ABSTRACT

A common effect of aging is decline in spatial cognition. This is an issue for all elders, but particularly for elder drivers. To address this driving issue, we propose a novel concept of an in-vehicle navigation display system that displays navigation information directly onto the vehicle's windshield, superimposing it on the driver's view of the actual road. An evaluation of our simulated version of this display shows that it results in a significant reduction in navigation errors and distraction-related measures compared to a typical in-car navigation display for elder drivers. These results help us understand how context-sensitive information and a simulated augmented reality representation can be combined to minimize the cognitive load in translating between virtual/ information spaces and the real world.

Author Keywords

In-vehicle navigation system, augmented reality, senior drivers, windshield-based display, cognitive mapping.

ACM Classification Keywords

H.5.1 [Information Interfaces and Presentation (e.g., HCI)]: Multimedia Information Systems—*Artificial, augmented and virtual realities*

INTRODUCTION

As our society is aging, the number of elder drivers (drivers over the age of 65) is rapidly growing. These individuals' quality of life is acutely linked with their ability to maintain independence in mobility [17]. While there is a decrease in the number of work and business-related trips they take, daily trips for shopping and multipurpose trips for various social activities increase with age [3]. Nevertheless, they may be forced to abandon these trips and have a reduced sense of independent mobility due to decreased cognitive ability and difficulty in interacting with navigation devices [9] that could potentially help address declines in driving ability. This reduced mobility has a substantial impact on the individual, their family who often takes on the burden of lost mobility independence, and social interaction activities [10].

There is consistent evidence that *spatial cognition ability* declines with increasing age. Particularly, older adults have more difficulty in cognitive mapping, the ability to accurately represent a spatial environment mentally, and way finding, the ability to navigate efficiently in an environment. For example, it has been found that older adults have difficulty in understanding and using 'you-are-here' maps [20].

Fortunately, these driving-related issues can be lessened by applying situational awareness and providing navigation guidance that can support decision making of drivers. For example, with a GPS-based navigation system, drivers can more easily access and act on current and future driving information (*e.g.*, information about the local road network, information about upcoming road conditions, and which road to turn onto to get to a destination) and be more confident in turning onto the correct road in intersections or complicated forked roads.

At the same time, however, providing such in-vehicle information does not only add to task complexity but it also creates issues with *divided attention* in having to focus on both the information display and the road, and extra cognitive load in matching the computer-generated streets on the GPS system to the real streets in the 3-dimensional perspective that drivers have. Even putting aside their unfamiliarity in operating such systems, this added mental effort is a more problematic barrier to overcome for elder drivers than for younger drivers. Not surprisingly, technologies such as GPS systems are often considered to be too difficult to use to be a useful driving aid for elder drivers [7], despite their seeming promise to support the mobility of elders.

To overcome these problems with existing GPS systems, we propose a concept of windshield-based 2.5-dimensional in-vehicle navigation display system (see Figure 1). An augmented reality projection is used to minimize the issues with divided attention and cognitive load by overlaying driving directions on the windshield (and road), making it easier to focus attention in one location and to translate between the virtual/information space of the navigation

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Figure 1. Screenshot of the simulated windshield-based 2.5 dimensional in-vehicle navigation display system.

system and the real world. The results of an evaluation of a simulation of our novel windshield-based display compared to the typical display of a personal navigation device with 24 subjects (12 elder drivers (65+) and 12 younger drivers) demonstrated that our display induces less divided attention and fewer navigation and driving errors. While these results hold for younger and elder drivers, they are especially true for elder drivers. In addition, elder drivers prefer our display over traditional in-vehicle navigation systems (75.0%) and find it more intuitive (83.3%).

This paper is structured as follows: we begin with a discussion of divided attention and cognitive load and how augmented reality can be used to address these for drivers. We review related research on augmented reality-based in-vehicle information displays and then present a detailed description of our proposed windshield-based navigation display. We then describe the virtual test-bed we developed for our user study, comparing our novel display to a conventional in-vehicle navigation device. We present our results that demonstrate our display's ability to improve driving performance for elder drivers and reduce divided attention issues for elder and younger drivers. We end with a discussion of our results and plans for future work.

PROBLEM FOCUS

Cognitive distance

Technology is giving us the ability to present information anywhere and anytime. Despite this ability, there is often a large gap or distance between physical spaces (*i.e.*, the real world) and virtual information spaces. Depending on the relevance of the information being provided, the method of conveying information, and the user circumstances, this distance may be small or large. With a large gap, a user may take more time and may have to expend more cognitive effort to adjust from one space to another. We refer to this gap as the *cognitive distance* between computing and physical spaces. There are two distinct components that comprise cognitive distance. The first is the cognitive effort required to move one's attention from the physical space to the information space, and to locate the appropriate information within the information space. The second component is the effort required to move back from the information space to the physical space and apply the extracted information to the task at hand. As the effort required for either of these components grows, the overall cognitive distance grows.

Furthermore, if users are required to switch between these two spaces frequently, the impact of the cognitive distance can be even greater. This is particularly true for people who either have a cognitive difficulty, or are completing a task that is time-sensitive or has a high cognitive load associated with it, and certainly applies to elder drivers who may be suffering from age-related cognitive decline.

Divided attention

Divided attention is the ability to respond simultaneously to multiple tasks or multiple task demands and is regarded as the highest level of attention [23]. The greater the cognitive distance, the harder it is to have divided attention across information and physical spaces. When users are unable to maintain divided attention, this is often referred to as the *split-attention effect* [2], and often occurs when the same modality is being used (*e.g.*, visual) by both the information and physical spaces. This suggests two important design issues: the types of information in the information space and the manner of presenting the information are important for reducing cognitive distance. The former can help users feel that they are not working on multiple tasks, but are working on one, focused task, making it easier to move between spaces and apply information. The latter can also help users in moving between spaces, and can help users to locate information in the virtual space.

There have been a number of driving-related studies that have examined the issue of divided attention from this information presentation perspective. One such study had younger and older drivers use a virtual driving simulator to drive a particular route while performing a secondary task: reading a series of four-digit numbers either superimposed on the windshield or displayed to the lower right of the driver on a portable display [11]. Older drivers performed much better in terms of controlling their vehicle and accuracy in reading the numbers with the windshield-based display. The problem with the portable display is that it caused drivers to switch their attention from the road to the display. As the task difficulty increased, the difference in performance between younger and older drivers also increased.

A subsequent study with subjects with traumatic brain injury and healthy individuals used the same basic experimental setup and method, but varied the time between the presentations of numbers and varied the location of the numbers on the windshield [8]. Both factors impacted performance on the primary and secondary tasks. From this we infer that cognitive load increases with variable workloads, which could result from many issues including timeliness of information, and that cognitive load increases when information is presented poorly and without context, either with respect to the presentation location or the content. Research on cognitive load from the aviation domain reinforces these lessons [6].

To summarize these results, in situations with variable workloads (*e.g.*, mobile settings) and that require timely responses or actions, cognitive load can increase. However, this can be reduced by selecting an appropriate manner for presenting information, and by presenting information that is context-sensitive and relevant to a user's primary task. We can apply these results to our problem: reducing the impact of divided attention and reducing cognitive load for elder drivers who have difficulty using navigation aids and may suffer from cognitive decline.

We will now discuss how these results relate to the two components of cognitive distance. Presenting information where users are already focusing their attention will reduce the effort required to shift attention from the physical space to the information space. Contextually presenting information and focusing on presenting only task-relevant information will make it easier to locate and extract appropriate information in the information space. Again presentation location can greatly impact the effort required to move back to the physical space. Finally, by presenting only task-relevant information, it will be easier for users to apply the information in the physical world.

AR-BASED IN-VEHICLE INFORMATION DISPLAYS

Recently, car manufacturers have been pointing to Augmented Reality (AR) as the next-generation visualization technology for in-car driving displays. It provides the necessary technology for displaying information where users' attention is focused in the car. Researchers have investigated the concept of projecting navigation instructions onto a video image of a road to make it easier for the driver to orient himself in complex traffic situations [16]. Others have shown that it is useful to have two views of the environment, an egocentric user view of the environment and an exocentric view of the whole 3D environment like an overview map [22]; further, cues for orientation and motion used in the real world will also be of great help for navigation. To this date, the focus on automotive HUD (Head-up display)-based AR visualization has been on technical challenges related to the compatibility of AR processing modules or producing reasonable image quality. Current commercial automotive HUD platforms mainly employ small displays so as not to interfere with drivers' abilities to drive safely.

Academics have investigated and evaluated a number of AR-based visualization concepts using mobile platforms or projector-based driving simulators [13, 14, 15]. One AR system combined GPS/inertial measurements with real-time road video footage to display highlighted road boundaries and surrounding vehicles in low-visibility conditions [15]. A number of solutions to solving the camera registration problem (*i.e.*, how to detect and track the road so images can be robustly projected upon it) have been built (*e.g.*, [5]), making it simpler to build such AR-based systems.

Other research has compared two information presentation approaches for focusing a driver's attention in difficult driving situations: a bird's eye view and an AR-based 3D arrow [19]. The bird's eye view unexpectedly performed better as the 3D arrow was not positioned well relative to the car's location and was hard for users to interpret. An interesting approach to presenting current location information is to use a trolley-cable-like line that appears as if suspended over the road [12]. While this supports simple and intuitive route guidance, it does not support global awareness (*i.e.*, a driver's understanding of nearby road networks). AR-based visualization has also been employed for the purposes of supporting navigation and perception in the cases of hidden exits or roundabouts [13], and for parking assistance and tourist guides [18].

From a review of the literature on in-vehicle AR-based display systems, we note that two significant informational aspects, global awareness and local guidance, are necessary for an effective navigation aid. As referred to in [1, 21], global awareness pertains to knowledge regarding the route to the destination, and local guidance is related to the tasks that involve controlling the vehicle and knowledge about the surrounding environmental situation. A large number of applications have focused on supporting local guidance using AR, particularly in driving situations such as low-visibility, upcoming dangers or visually-occluded roads. Most AR-based display systems, however, have focused on providing global awareness, mostly through use of a bird's eye view perspective. Very few systems attempt to incorporate both global awareness and local guidance. We now combine our understanding of cognitive distance and related work in augmented reality displays to describe our novel AR-based display for addressing cognitive distance.

SIMULATED AR WINDSHIELD 2.5D DISPLAY

Our navigation display has been designed with the ultimate goal of minimizing a driver's cognitive load and issues of divided attention induced in attending to both the real driving space and the virtual space of a GPS-based map visualization. Accordingly, we have mainly focused on two specific issues in our work. The first issue is how to improve a driver's ability to cognitively synchronize the dynamic images from driving and from a secondary display that are moving in two different coordinate systems with potentially different orientations and scales. The second is how to reduce issues of divided attention caused by the visual and spatial separation between the view of the actual road through the windshield and the secondary navigation display. While both issues impact all drivers, they certainly place an additional burden on elder drivers.

In our work, we assume that the technical challenges necessary for displaying images on an entire windshield and accurately registering these images to features of the road will be addressed in the near future by other researchers. This is not an unreasonable assumption since, as described in the previous section, researchers have had successes in tracking the road and projecting upon it in real-time [5] and auto manufacturers see whole windshield displays as *the* future of in-vehicle displays [4].

For our display, a computer-generated 2-dimensional map image of the area where the driver is navigating is

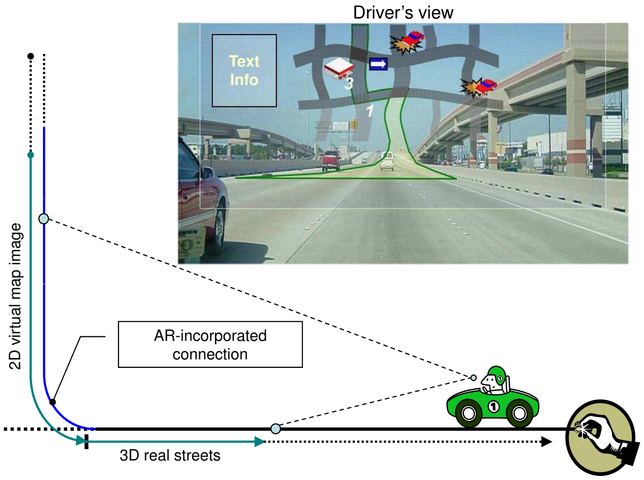


Figure 2. Concept diagram of AR-incorporated 2.5D navigation display on car windshield.

Figure 3. Experiment test-bed incorporated with a driving simulator with wheel joystick set and contactless gaze tracker.

dynamically displayed as if it is sliding down over the upper part of the windshield and merging into the real road (see Figure 2). By synchronizing this movement with the current car movement, we expect the driver to experience a seamless transformation of the display and its information into the real road. Further, this display should not only help elder drivers achieve an intuitive awareness of road network information near their location, but also has the potential to be useful for displaying contextual or local guidance information about the driver's location (*e.g.*, car accident, traffic congestion).

Our windshield-based display uses the same scale and orientation as the real streets viewed through the windshield. The map visualization also adapts to the current car position, allowing the local road network to be contained in the driver's view. This supports drivers in interpreting both the real and virtual spatial context in a single view. As a result, we expect our display to induce a lower cognitive workload and fewer issues of divided attention than current navigation displays. An important measure of cognitive workload is driving performance. As cognitive load increases, driving performance often decreases correspondingly. So, for the validation of our display, we form three hypotheses with respect to two metrics: driving performance and distraction due to divided attention.

- H1: When driving while dependent on any navigation system, elder drivers will exhibit worse driving performance and more issues of divided attention than younger drivers.
- H2: When using our simulated AR windshield display, the drivers will exhibit better driving performance and fewer issues of divided attention, than when using a typical in-car navigation device with a 2D bird's eye view map display.
- H3: When using our simulated AR windshield display, elder drivers will exhibit better driving performance and fewer issues of divided attention than when using a typical in-car navigation device with a 2D bird's eye view map display.

Regardless of a driver's age group, her primary task, driving, should not be impeded by other secondary tasks (*e.g.*, referring to in-vehicle information systems); that is, the display systems should not generate any excessive distraction while supporting enhanced navigation. While we expect the simulated AR windshield display to be effective in aiding elder drivers' navigation abilities, highly-visualized in-vehicle information media may cause unexpected driver distraction. In actuality, both display types have different features that may lead to potential distraction. In typical in-car navigation devices, frequent separation of attention from the real driving view (*i.e.*, divided attention) is required for a driver. On the other hand, in our simulated AR windshield display, the computer-generated images dynamically superimposed on real driving view portion (*i.e.*, overlapped images) can attenuate the driver's attention in concentrating on traffic situations.

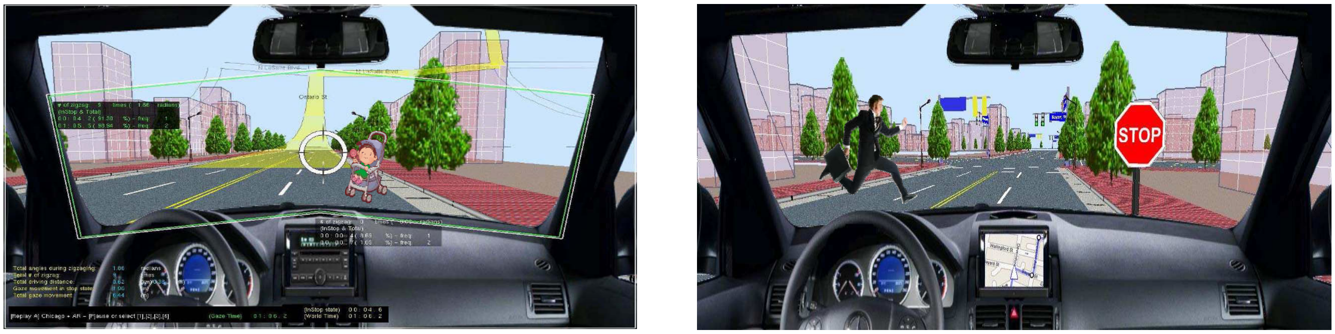
EXPERIMENTAL DESIGN

We now describe the experiment we conducted to validate our hypotheses.

Test-bed setup

We implemented a driving simulator, using OpenGL, to conduct our experiment, due to the safety issues of conducting an experiment in live traffic environments as well as the technical challenges of implementing a full windshield-based high resolution HUD platform in a car. Geospatial information from Google Maps is graphically rendered in this simulator on a 26-inch widescreen LCD HDTV (16:9 aspect ratio) for both Pittsburgh and Chicago. Subjects navigate through the simulated cities using a wheel joystick and two foot pedals (see Figure 3).

For each city, each subject experiences two different simulated visualizations, our AR-based windshield display



(a) AR windshield navigation display (ARD in data analysis mode) (b) GPS-based navigation display (RD in test mode)

Figure 4. Our study simulations.

(ARD, Figure 4(a) where the text, an eye-gaze tracking cross and secondary display zone boundaries for data analysis were not shown to participants) and the 2D bird's eye view map display mode (Figure 4(b)) regularly employed in typical GPS-based navigation systems (RD, from 'regular display') usually installed to the lower-right of a driver's head. (Note that we conducted a small survey of the common placement of navigation systems and found that the most common location was to the lower-right of a driver's head.) Each driver participates in 4 different driving task conditions: AR-based windshield display (ARD) for Chicago and Pittsburgh and regular GPS-based display (RD) for Chicago and Pittsburgh, in a counterbalanced order based on the Latin square method.

For each task, a highlighted route that is 3.36 km long is displayed using either the ARD or the RD. Subjects are expected to refer to it as they navigate from the starting position to their destination, typically as they navigate through intersections. They need to obey traffic signals and common driving rules (*e.g.*, stay on their side of the road and avoid the sidewalks). Each presented route includes 12 intersections: 4 right turns, 4 left turns and 4 to go straight through. In the case of missed turns, a U-turn needs to be made to get back on the route again. In addition, during each driving condition, they will encounter 12 signal lights, 3 stop signs, 5 pedestrians (baby in a baby carriage) crossing the road from right to left and 5 other pedestrians (man wearing a business suit, holding a suitcase) which they are expected to avoid.

The driving input from the wheel joystick and foot pedals provided by each subject is automatically recorded for later analysis of driving performance, our proxy for real-time cognitive load. In particular, our measures are task completion time, number of missed turns, number of interactions with pedestrians, and the number of signal light/stop sign violations.

To assess whether drivers have issues with divided attention, we track their eye gaze to see where they are looking. We employ the Smart Eye Pro 4.5 contactless gaze tracker to observe where subjects have been looking (gaze location) while driving (See Figure 3). In particular, we calculate the overall distance traveled by the eyes, average eye movement speed and the number of times and time spent looking away from the primary driving view (outlined in Figure 4(a), above the dashboard to below the rearview mirror). Gaze distance and speed are measures of how noisy the eye gaze movement is, and can indicate the degree of divided attention. While conducting our experiments, we observed drivers stopping the car the re-orient themselves, particularly after making a driving mistake (*e.g.*, running a red light). Therefore, we report these gaze measures both over the total driving task time and when the driver is in motion. A post-questionnaire and interview is used to get a qualitative understanding of users' feelings about both displays and how the displays impacted their driving.

Experimentation constraints

Before discussing our results, we will first describe some of the limitations of our experimental setup. First, our current focus is on the user interface concept rather than on how it can be applied in a real optical-see-through windshield display for a final product. In this first study of our novel display, the test-bed has been implemented as a '*simulated*' AR windshield display prototype; therefore, its simulated visuals would differ from those seen in a real car, from a cockpit-based platform or from a system that used videos rather than graphics. However, prior studies reporting a relationship between divided attention and driving were mostly based on correlation analysis between psychometric tests and behind-the-wheel driving observations rather than a direct examination of driving behaviors. As a result, our current experimentation was framed on an already-demonstrated basis that using graphical simulations can manipulate divided attention tasks, and allows actual driving measures such as speed and lane deviation to be used. Our approach allows for an objective and direct evaluation of the relationship between cognitive impairment (*i.e.*, divided attention) and functional performance (*i.e.*, driving), as addressed in [8] and [11], which also used driving simulators. In addition, to more easily compare the route guidance capabilities of the two displays, we controlled a number of experimental factors such as the number of traffic incidents a driver experiences, number of turns, length of the driving route, location of the RD installation position (based on our survey), and realistic optical distortion or field of view (as opposed to our 0.58m × 0.325m simulated display at a distance of 0.6m approximately, providing a horizontal view of 52° and a vertical view of 30°) as in those of a real windshield, leaving variations of these to our future work. The distance subjects sat from the display meant that the eye gaze space was smaller than in a real driving situation, but this does not impact the comparison of the two displays, although it tends to reduce overall eye gaze movements. Changing the location of the RD to just above the dashboard, another common mounting location, would likely positively impact the driving performance and divided attention of our subjects. Similarly, increasing the number of traffic incidents would likely negatively impact these factors, as it would be more difficult for subjects to distinguish between the traffic incidents and the actual road.

Next, in order to better understand the impact of displays on divided attention, we examined several aspects of our subjects' eye gaze movements. However, truly measuring divided attention is quite challenging. For example, we tried to define a '*secondary display zone*' to designate the zone where a driver's mental focus is not on the road. Accordingly, we defined the upper boundary of the '*secondary display zone*' much lower than the top of the windshield. However, it was not lowered up to the horizon because, in our pilot studies, drivers often glance at simulation elements such as signal lights and pedestrians in the area between current upper boundary and the horizon. In an ideal case, we would be able to determine the factor that caused the driver to focus on a particular part of the display, particularly where the simulation elements and the map are semi-transparently overlapped. We did try to divide the space into a larger number of sub-zones; however this was still insufficient to confirm that a driver's mental focus was taken off the road and the primary driving task. As a practical approach, other physiological measures like heart rate or pupil diameter variability can be employed; however, at this stage of our research, we chose not to use intrusive sensing to avoid imposing fatigue or discomfort on our elderly subjects. In the end, we defined the '*secondary display zone*' as shown in Figure 4(a).

Participants

We recruited 24 subjects for our experiment. This included 12 elder drivers, over the age of 65 (range/mean/SD: 66-85/74.25/5.48), and 12 younger drivers (19-41/30.42/5.68). At the beginning of each experimental condition, all of our subjects received the exact same pre-written textual instruction. Other than a gaze calibration step at the beginning of the experiment and the questionnaire at the end, there was minimal, if any, experimenter interaction with the subjects. 13 of our subjects were female and 11 were male, with the gender distribution being almost equal for the different age groups. Our subjects were split in terms of their experience with GPS navigation systems, with 13 experienced users, including two elder drivers, (marking on a pre-survey: '*only when needed*', '*very often*' or '*almost every time driving*') and 11 with very little experience, including one younger driver (selecting '*never*' or '*very rarely*'); however the relative inexperience of our older subjects with GPS systems does not impact the comparison of the two displays for the older subjects.

EVALUATION RESULTS AND DISCUSSION

We present the results of our experiment by comparing the driving performance and gaze movement results for our different age groups, different display modes, and the interactions between these two factors. We have conducted a two-way ANOVA for repeated measures ('*age group*' as one between-subjects factor × '*display mode*' as one within-subjects factor) and then conducted the post-hoc contrast tests. Note that '*city*' was not considered as a separate variable in our analysis because all traffic- & street- related configurations were the same for both cities. We used multiple cities to avoid our subjects being too familiarized with the streets. An analysis using '*city*' as a factor revealed no impact.

H1 - Comparison by age group: Elder drivers (E) vs. younger drivers (Y)

Our first hypothesis was that elder drivers (E) will have worse driving performance and exhibit more signs of divided attention than younger drivers (Y), when driving with either in-car navigation display.

As expected, there were significant differences between the two age groups for most of our measures related to driving performance and gaze results (See Table 1.). The average driving time of older participants is 1.90 times longer than younger drivers, F(1,22)=42.03, $p<.0001$. There were no significant differences in the number of traffic signal and stop sign violations, nor in eye gaze movement speed. The number of incidents with pedestrians in danger was 1.81 times more than that of younger drivers but this was not significant (F(1,22)=2.97, $p<0.0990$); nevertheless, elder drivers had 2.38 times the number of missed turns (F(1,22)=4.36, $p<0.0486$) and 1.78 times the number of eye gazes away from the road and on our secondary display zone (F(1,11)=8.05, $p<0.0162$) than younger drivers. (*cf.*, the means of the driving time and gaze time look proportional; however we found the correlation coefficient between these to be 0.387, that is, the actual data of individuals is not.) Based on these results, we can say that the hypothesis 1 is supported.

H2 - Comparison by display mode: ARD vs. RD

Our second hypothesis is that using the ARD will result in better driving performance (*i.e.*, fewer missed turns and fewer pedestrian-related accidents) and fewer issues with divided attention (*i.e.*, less gaze focused on the secondary display zone).

Our ARD, the windshield-based display, did result in better driving performance and fewer issues with divided attention across most measures when compared to the RD, the typical GPS-based navigation display (See Table 1). Drivers using the ARD completed the driving tasks significantly faster, F(1,70)=7.21, $p<.0090$). The ARD resulted in fewer (by almost half) missed turns, F(1,70)=4.88, $p<0.0305$,

Display & Age Group	Augmented Reality Display (ARD)			Regular Display (RD)		
Measures	**Y(μ)**	**E(μ)**	**Total(μ)**	**Y(μ)**	**E(μ)**	**Total(μ)**
The number of driving datasets	24	24	48	24	24	48
Driving time (*mm:ss.0*)	05:31.6	10:01.4	07:46.5	05:36.1	11:11.4	08:20.2
in motion state	04:41.1	08:41.1	06:41.1	04:50.0	09:42.7	07:16.4
in stop state	00:50.4	01:20.4	01:05.4	00:46.2	01:28.7	01:07.4
Missed turn count	0.25	0.42	0.33	0.33	0.96	0.65
Pedestrian in danger count	0.21	0.29	0.25	0.42	0.83	0.63
Unobeyed traffic signal & stop sign count	0.42	0.58	0.5	0.42	0.21	0.31
Total gaze time in the secondary display zone (*mm:ss.0*)	00:15.1	00:16.8	00:15.6	00:52.5	01:27.1	01:03.2
in motion state	00:10.3	00:14.6	00:11.6	00:40.8	01:15.2	00:51.4
in stop state	00:04.8	00:02.2	00:04.0	00:11.8	00:11.9	00:11.8
Count of gazes to the secondary display zone	41.28	72.38	50.85	116.72	190.25	139.35
in motion state	30.28	61.88	40.0	94.28	159.88	114.46
in stop state	11	10.5	10.85	22.44	30.375	24.88
Time per gaze in the secondary display zone (*sec/gaze*) in motion state	0.34	0.25	0.32	0.42	0.46	0.44
Total gaze movement distance (*m*) in motion state	37.88	72.77	48.62	48.69	99.11	64.21
Gaze movement speed (*m/sec*)	0.14	0.16	0.15	0.18	0.19	0.18
in motion state	0.14	0.15	0.14	0.17	0.18	0.17

Table 1. Average measures for each age group (Y=Younger, E=Elder) and display mode.

and fewer (more than half) dangerous encounters with pedestrians, F(1,70)=7.63, $p<0.0073$. It also resulted in 23.0% and 24.3% less gaze movement distance for the total driving time and for in-motion driving time, respectively (F(1,37)=12.56, $p<.0001$ and F(1,37)=7.55, $p<.0001$). Subjects' gazes were focused on the secondary display zone by a factor of 2.86 fewer times (F(1,37)=59.58, $p<.0001$) and spent less time (factor of 4.43 times, F(1,37)=45.73, $p<.0001$) doing so while moving. In addition, gaze movement speed was significantly less (F(1,37)=41.37, $p<.0001$); that is, participants' gazes are less busy or noisy. However, drivers have lower performance for traffic signals and stop signs when using the ARD, although the difference is not significant (F(1,70)=1.71, $p<0.195$). These results demonstrate that the ARD generally results in better driving performance while causing less distraction. However, our primary display zone includes areas above the road (See Figure 4(a)). Gazes in the primary display zone might not necessarily be related to the primary driving task when using the ARD; that is, despite having fewer issues with eye gaze focus in our secondary display zone, the ARD might attenuate the driver's attention when trying to concentrate on traffic situations (as we noted earlier). Our subjects did not mention this during the exit interviews, and the ARD still resulted in better driving performance results. We conclude that hypothesis 2 is supported.

H3 - Comparison: age group × display mode

Our last hypothesis is that elder drivers using the ARD will have better driving performance and fewer issues with divided attention, than when using the RD. In other words, we are looking at the question of whether changing the representation of navigation information has positive effects on the people who feel increased mental workload while driving, by aiding navigation without increasing distraction.

In this comparative analysis, we conducted post-hoc contrasts following up our two-way ANOVA results with respect to four subgroups categorized according to age group and display mode: *younger group* and *elder group* × *ARD* and *RD*. Among the four subgroups, younger drivers using the ARD had the best results across most of our measures, while elder drivers using the RD had the worst (See Table 1).

For younger drivers, there was no driving performance related differences between the two displays. However, when using the ARD, there was significantly less impact of divided attention for all of our gaze-related measures. That is, for younger participants, the ARD mainly exerted an effect on distraction reduction, and not on navigation performance improvement. On the other hand, elder drivers saved almost 70 seconds of the driving time (time in motion) (F(1,70)=12.68, $p<0.0007$) with significant reduction in

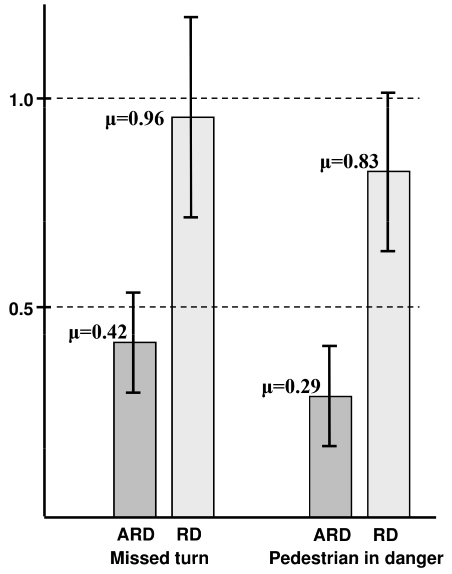


Figure 5. Senior drivers' missed turn and pedestrian in danger counts using the ARD and RD.

the numbers of missed turns and pedestrians in danger when using the ARD (factors of 2.29 times and 2.86 times fewer, F(1,70)=7.33, $p<0.0085$ and F(1,70)=7.96, $p<0.0062$ respectively; see Figure 5). Further, the gaze time in the secondary display zone is 5 times less than when using the RD (F(1,37)=29.27, $p<.0001$). In addition, there are significantly fewer instances of gazes into the secondary display zone (factor of 2.62 times; F(1,37)=31.49, $p<.0001$) with a slower gaze movement speed (F(1,37)=14.50, $p<0.0005$). The average gaze duration in the secondary zone was 0.54 times shorter (F(1,37)=6.3905, $p<0.0159$). Interestingly, the elder group using the ARD had a shorter amount of gaze time (F(1,37)=10.71, $p<0.00023$) and there were a smaller number of gazes (F(1,37)=5.98, $p<0.0193$) into the secondary display zone than the younger group using the RD.

Based on these results, we conclude that our ARD has been more effective in enhancing elder drivers' navigation performance while causing less divided attention than the RD; hypothesis 3 is supported.

Qualitative results

Now that we have examined the objective results of our study, we will present the subjective and qualitative results from our questionnaire and interview.

Post-questionnaire

Participant responses from the post-questionnaire reflect the results of the quantitative analysis. We asked participants to rate on a 5-point Likert scale, which display was more helpful in being: Q1) *easier to discriminate the road to take in front of intersection*, Q2) *easier to look over upcoming road network around the route highlighted*, Q3) *less distracting in responding to signal lights*, Q4) *less distracting in responding to pedestrians crossing the roads* and Q5) *easier to know where I am now driving*. On our scale, '*1*' corresponds to the RD being much better and '*5*' correspond to the ARD being much better.

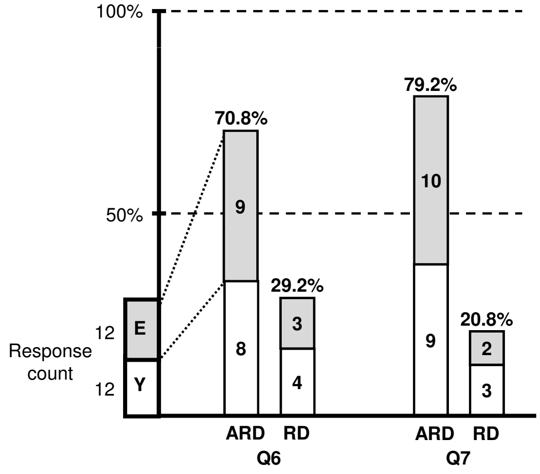


Figure 6. Overall system preference by age group.

The first two questions, Q1 and Q2, are related to two fundamental elements of effective navigation aid. For the local guidance (Q1), more than 70% of our subjects preferred the ARD to the RD with a rating average of 3.96. 66.7% of the elder drivers rated the ARD as a '*much better*' display. For the global awareness (Q2), 58.3% in each age group (and overall) rated the ARD as a '*much better*' display. Older participants felt more comfortable navigating when using our display, especially in the aspect of local guidance. Next, Q3 and Q4 relate to being responsive to traffic events. Most of the older participants had '*no preference*' for these aspects (58.3% and 41.7%, respectively), while the younger participants slightly preferred the RD (58.3% and 50.0%, respectively). However, 33.3% of elder participants thought the ARD was a '*much better*' display for supporting less distractive driving in responding to pedestrians. These results correspond with the performance results on pedestrian- and traffic signal-related measures (Table 1). Q5 relates to a driver's increased awareness of his/her location and navigation information. 58.3% of older participants and 41.7% of younger participants rated the ARD as a '*much better*' display.

Lastly, each subject was asked to specify an overall preference from the two displays. Two direct questions were asked: Q6) '*which display would you want to use?*' and Q7) '*if you could easily turn the displays on/off so you are free from safety problem, which display would be more intuitive to use during driving?*'. 70.8% and 79.2% of all participants selected ARD as their preferred navigation display to use and as being more intuitive, respectively (See Figure 6). Looking at the different age groups, elder drivers preferred the ARD (75.0% and 83.3%, respectively), as did younger drivers (66.7% and 75.0%, respectively).

Post-task interview

In a post-task interview, we asked subjects to comment on the relative merits and issues with the displays they used. We also asked them for opinions on what improvements could be made to the displays. The results of our interviews reflect our quantitative and questionnaire-based results.

Elder drivers, in particular, expressed appreciation for our augmented reality windshield-based display. Several commented that when we first demonstrated how to use the two displays, they thought the more conventional navigation display would be better to use. They had seen this type of display in their children's cars and it looked familiar to them even though they had little or no experience with it. However, as they used the RD, they realized that they had to look away from the street to view the display, on a frequent basis and this was distracting. They liked the fact that the ARD allowed them to look at both the navigation display and the street at the same time and that they were arranged appropriately from a spatial perspective. Elder drivers mentioned that this made it easier to notice pedestrians crossing the street. However, they also commented that if a navigation aid obstructed their ability drive safely even a little bit, they would be unlikely to use it. On a related issue, our subjects liked being able to effectively turn off the RD by not looking at it, when the demands of the driving task were high. The ability to selectively turn on and off the ARD was a feature our subjects said they wanted.

Our subjects had difficulty, at times, in understanding the ARD visualization. All of the ARD visuals are superimposed on top of the real street scene (*i.e.*, the street scene graphic layer is always rendered before the ARD visuals are placed on top). This caused some drivers to misinterpret the depth of the added visualization. For example, the ARD visualization shows all upcoming intersections and side roads vertically up the windshield (the further the intersection, the higher up the windshield it is), which means that upcoming side roads are superimposed on top of buildings and the street. This gave the impression that all the side roads will actually appear before the driver reaches a building. Because of this, when the visualization indicated an upcoming turn, some drivers made errors and turned at an earlier intersection than the one they were supposed to turn at. Other drivers commented that when the visualization indicated that they go straight (via a highlighted path that rises vertically up the windshield), they thought that meant they could continue to go straight, regardless of the state of the traffic lights.

Other subjects commented on the desire for additional situational information in the visualization. One younger female participant said she forgot to make some turns: if there was a red light at the intersection where she should make a turn, she waited there and then went straight when the light turned green. Our driving simulator did not provide a physical turn indicator or a visualization that the driver intended to turn (typically a blinking arrow in real vehicles), which could have been used to remind her of the turn. Further, the highlighted yellow route in our ARD visualization almost fades completely as it approaches the driver's actual location, merging with the real road.

Another subject spoke to herself about the next action she should take at each intersection. She even acted out using an invisible turn signal indicator. A real physical lever along with a virtual light on the dashboard could have helped her in remembering what actions to take, rather than holding this information internally. On a related note, many of our participants wanted the ARD to more visibly indicate the next action they had to take (using a superimposed arrow, for example) and the current state of upcoming traffic signals. Older drivers also requested a pedestrian warning system and larger street signs that were more legible. These requests all point to additional information that could be visualized through our ARD, and changes that could be made to our experimental simulator setup.

CONCLUSION

In this study, we have proposed a novel windshield-based 2.5-dimensional in-vehicle navigation display system to aid driver's in reducing issues of divided attention from having to switch between navigation system and the real road view, and reducing cognitive load from having to cognitively map computer-generated map information of the navigation system onto a driver's real road view. In an evaluation of simulations of this display and a typical GPS navigation display, 24 subjects, 12 elder and 12 younger drivers, participated in a virtual driving experiment. Our results show that the drivers using our display system have significantly fewer navigation errors and divided attention-related issues when compared to using the regular display. Most importantly, we have demonstrated both quantitatively and qualitatively that these results hold for elder drivers who are more likely to have difficulty in cognitive mapping and way finding.

In this work, we have mainly focused on validating the effectiveness of our novel display system compared to an existing navigation display. In our future work, we would like to make the improvements noted in our evaluation, and explore more focused design guidelines for supporting older people's navigation preferences and perceptual abilities. We would like to explore variations in our experimental setup, including increased traffic to create more realistic driving situations making it more difficult to differentiate between the visualization and traffic, variable location of the in-car navigation display, and using physiological sensors to determine cognitive load. To enhance driver's situational knowledge, we would like to understand the impact of adding information about real-time traffic (*e.g.*, traffic jams, car accidents) can be presented with local area information (*e.g.*, gas stations, local landmarks or attractions) on the road network image in our system. Additionally, considering other divided attention factors in vehicles, we will consider how to use our display to represent information typically displayed on dashboards or reflected on side/rear mirrors. Finally, we will incorporate our display system into a full windshield-based optical see-through HUD platform donated by General Motors, for real testing in a vehicle.

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