INVITED PAPER

Behind the Glass: Driver Challenges and Opportunities for AR Automotive Applications

This paper presents challenges of incorporating augmented reality into automotive applications and promising research solutions.

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ABSTRACT | As the automotive industry moves toward the car of the future, technology companies are developing cutting-edge systems, in vehicle and out, that aim to make driving safer, more pleasant, and more convenient. While we are already seeing some successful video-based augmented reality (AR) auxiliary displays (e.g., center-mounted backup aid systems), the application opportunities of optical see-through AR as presented on a drivers' windshield are yet to be fully tapped; nor are the visual perceptual and attention challenges fully understood. As we race to field AR applications in transportation, we should first consider the perceptual and distraction issues that are known in both the AR and transportation communities, with a focus on the unique and intersecting aspects for driving applications. This paper describes the some opportunities and driver challenges associated with AR applications in the automotive domain. We first present a basic research space to assist in these inquiries, which delineates head-mounted from heads-up and center-mounted displays; video from optical see-through displays; and world-fixed from screen-fixed AR graphics. We then address benefits of AR related to primary, secondary, and tertiary driver tasks as well as driver perception and cognition challenges inherent in automotive AR systems.

KEYWORDS | Augmented reality (AR); displays; human factors; intelligent transportation systems

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I. INTRODUCTION

We are already seeing some limited, but successful automotive augmented reality (AR) systems in the market today. A handful of manufacturers offer a video-based AR auxiliary display to aid drivers in maneuvering the vehicle and identifying potential hazards while backing up. In the near term, we can expect manufacturers to build upon these technologies and offer other video-based AR applications. Moving forward, the application opportunities of optical see-through AR as presented on a drivers' windshield is a likely reality, yet to date it has not been fully developed for commercial consumption. This may be in part due to the difficult technical, usability, and cost issues related to fielding this capability.

As we move toward the car of the future, the synthesis of technology and lessons learned from the AR, head-up display (HUD), aviation, and automotive domains will allow meaningful content to be displayed via AR-enabled windshields, displaying, for example, driving directions, notifications, cues for impending hazards; all without requiring drivers to take their eyes off the road. However, as we look to field AR technologies and applications in transportation, manufacturers and developers must take care to adequately consider the numerous perceptual and distraction issues that may be introduced, and they have been noted in these research and application domains. This is particularly important for driving applications where safety is paramount.

This paper describes interactions, opportunities, and challenges associated with applying AR interfaces in the automotive domain. Fig. 1 (based on [1]) depicts a conceptual representation of our research space and shows where the opportunities and challenges presented herein fit within a larger man–machine–environment system. While there are many opportunities and challenges to be studied within the space, this paper focuses on representative

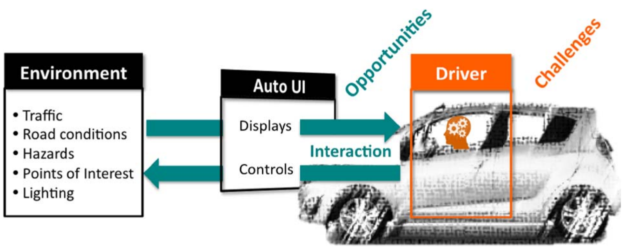

Fig. 1. ***Conceptual space for framing AR opportunities and challenges associated with automotive applications that include a human (driver), a machine (automotive user interface), and a driving environment.***

opportunities associated with driver interaction tasks (primary, secondary, and tertiary tasks), and specific challenges related to visual perception and driver attention.

First, we present related work on developing AR applications for automobiles (Section II). Then, we address unique issues related to users, interfaces, interactions, and evaluation methods (Section III), followed by a discussion of opportunities and challenges across several perceptual and cognitive areas (Sections IV and V). We close with some general conclusions and design suggestions. We have purposefully chosen to breadth over depth in the discussion of these topics as a means to introduce the most important AR visual and attention issues to those developing AR automotive applications, with the understanding that more detailed information on these topics is available via cited and related literature.

II. RELATED WORK

The University of Minnesota Intelligent Transportation Systems (ITS) Institute equipped ten buses with an AR-based driver assistance system that includes optical see-through HUD conveying conformal imagery to assist drivers in collision avoidance [2]. The system uses front bumper-mounted light detection and ranging (LIDAR) to detect nearby vehicles, which are then highlighted using red (nearby) and white (adjacent lane) AR rectangular outlines. The system also augments the lane markings, to assist the driver in maintaining the vehicle's lateral position in the narrow, bus-only shoulder lane during demanding weather and traffic conditions.

Medenica *et al.* [3] investigated the usability of emerging navigation aids to compare their impact on driving. They conducted a user study in a high-fidelity driving simulator with HUD, street-view device display, and traditional map-based GPS device display. For the HUD, they used conformal route information. They evaluated driving performance (as measured by lane position, steering wheel angle, speed, and number of collisions), visual attention (as measured by gaze direction), drivers mental workload (as measured by NASA–TLX), and subjective preference. The experiment shows that AR HUD exhibits the least negative impact on driving as compared to the other display devices.

Tonnis *et al.* performed user study in a driving simulator to investigate new AR visualization schemes for drivers' safety information and cues [4]. The HUD shows a virtual braking bar and drive path overlaid on the road. Their experiment revealed that AR information supported driving performance without increased mental workload and was preferred by participants.

Even though most research groups conducted user studies with prototypes in driving simulators due to difficulties in implementing hardware and conducting safe user studies, the laboratory for intelligent and safe automobiles at the University of California conducted a user study that utilized a full size windshield as an optical see-through display on an actual roadway [5]. Their work showed that AR graphics to convey a speeding alert reduced driver distraction and reaction time to the alerts.

There are currently some commercially available AR applications on the market of note. BMW vehicles are equipped with HUD showing screen-fixed navigation instructions, speed, and lane departure warnings in a limited area of the windshield [6]. The virtual cable superimposes a navigation route on the windshield hovering above the car using a volumetric display technology to convey the route [7]. Pioneer's Cyber Navi, which flips down in front of a driver's field of view (much like a sun visor), displays a navigation route, information of point of interests, and driver safety information based on computer vision technology [8]. Ideally, world-fixed displays would make use of the driver's entire field of vision. To our knowledge, this has not yet been realized in commercial products. Nevertheless, conformal optical see-through HUD functionality has been implemented and, despite small display areas, it yields significant benefits for drivers. However, the effects of AR information on driving performance, safety, and mental workload are still largely unknown or not fully understood.

III. USER INTERACTION IN AUTOMOTIVE AR APPLICATIONS

A reasonable starting point to examine automotive AR challenges is to first apply the available body of knowledge from general AR applications to the driving context. Below we consider the unique aspects of automotive AR applications with respect to users, interactions, interfaces, and evaluation methods.

A. Users

The demographic diversity of drivers and other in-vehicle users of handheld and head-mounted devices should be taken into account. For example, in the United States, a large population of elderly drivers may need additional cognitive and visual support since these drivers are at higher risk for motor vehicle crashes in challenging driving environments due to age-related visual, cognitive, and physical impairments [9]. The diversity of users' capabilities presents unique constraints on AR application design in vehicles, and suggests that a one-size-fits-all approach to design may not be effective for all user classes.

B. Interactions

Unlike traditional application settings, where the main task is to operate or attend to the application, drivers must instead focus primarily on the road and maneuvering the vehicle and thus cannot (and should not) allocate all attention resources to interactions with AR applications. In understanding the role of AR in driving, we consider the characteristics and relative priority of primary, secondary, and tertiary tasks in which AR may support [10]. Primary tasks are centered on how to cognitively and physically maneuver the vehicle including wayfinding, control of heading, control of speed, and managing distance to other cars or objects, to name a few. Secondary tasks are mandatory functions that can be associated to the primary task, such as initiating a turn signal, activating windshield wipers to increase visibility, etc. Last, tertiary tasks, such as adjusting the air conditioning, information, and entertainment functionality, and a host of other tasks are not directly related to driving, but still need to be supported in design. Since drivers have a limited set of cognitive and motor resources available for interaction with the suite of vehicle and personal interfaces, it is likely that effective AR automotive interfaces will register visual information on real objects in support of primary and some secondary tasks.

C. Interfaces

Driver vehicle interfaces are typically placed in physically separate areas of the driver's compartment to support effective performance of primary, secondary, and tertiary tasks (Fig. 2) [11]. Ergonomic design of driver interfaces allows users to perform their primary, secondary, and tertiary tasks with relative comfort, by placing controls and information at appropriate distances according to task priority. For example, primary tasks are supported by the forward-looking field of view and immediate reach (steering wheel and foot pedals), secondary tasks require some visual adjustments (e.g., redirection of gaze, change of focus and accommodation), and tertiary tasks often require both physical reaching and greater visual distraction. Since primary tasks focus on direct interaction with the outside world, augmented information to support the driving task may be best displayed in a head-up manner, e.g., via the windshield. If we are to design AR applications to support entertainment or social interactions, this information should be located in the tertiary task locations, and not interfere with the primary driving task.

We can further conceptualize the design space for automotive AR interfaces from the hardware (head-up, head-mounted, and device displays) and users' view perspectives (screen-fixed and world-fixed AR graphics), as shown in Fig. 3. Screen-fixed AR graphics are rendered at a fixed location on the display screen, and generally are not perceptually "attached" to any specific objects in the user's field of view. Conversely, world-fixed AR graphics, also termed conformal graphics, perceptually appear to be "out in the real environment," usually placed (in software) at a particular geolocation in order to annotate or draw attention to a real-world object of interest. This conceptual space is useful when considering the suite of available options for automotive AR applications. For example, world-fixed head-up optical see-through displays are likely best suited to present information related to the primary task, such as wayfinding, driving instructions, and imminent hazard warnings. Screen-fixed HUD could be used to display information not directly attached to objects in the

Fig. 2. ***Primary (red), secondary (teal), and tertiary (orange) task interface locations in a typical consumer automobile.***

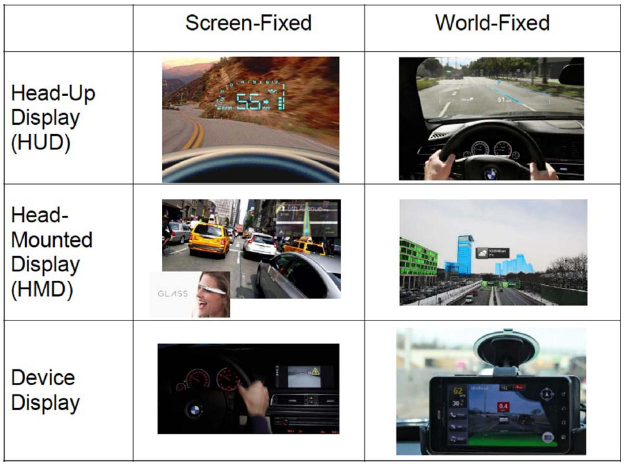

Fig. 3. ***Conceptual design space to assist automotive AR application design. AR information can be screen fixed or world fixed using a variety of devices and technologies to support driver tasks. Some device/graphics combinations are likely to be better suited for certain tasks than others. For example, world-fixed (conformal) AR information on HUD is likely suitable in support of primary, but not tertiary, tasks.***

real-world scene but still important for driving such as vehicle speed, fuel level, and engine temperature. Video-based center console displays that employ rear-mounted video cameras are already in use to support safely backing up (a primary task, but usually located in the center of the automobile console). Moreover, handheld device displays for passengers could be synchronized with a head-up driver display or center console displays to support collaborative wayfinding in busy environments that otherwise put large demands on drivers' cognitive resources. While there is ample opportunity for application in each of these spaces, the majority of the opportunities and challenges presented herein refer to world-fixed, head-up, optical see-through automotive AR displays.

Despite the display hardware or graphics approach, when designing AR applications, we should limit the time required for drivers to take their hands off the steering wheel as well as the degree to which visual attention is shifted off the road. It is likely that the most effective interfaces will not require supplementary input devices to attend to, such as sophisticated 3-D device-based user interfaces, suggesting that integration of voice-based natural language technology should be further be explored.

D. Evaluation Methods

Another unique aspect of creating AR applications for automobiles are the methods for design and evaluation. In addition to traditional usability and performance assessment of specific AR applications, we must also evaluate the applications' affect on driver performance, workload, and awareness. For this, we can employ extant methods from the transportation domain. For example, driving performance can be measured by motor or tracking performance, errors, and reaction time [12], while drivers' workload can be assessed using self-reported, performance-based, and physiological measures [13].

Another difficulty lies in the need to iteratively design and evaluate these interfaces in ecologically valid settings—that is, on the road—where conducting safe user studies may be challenging. Therefore, a combination of evaluation methods may be used, employing, for example, laboratory studies (e.g., peripheral detection task at the desk), static simulators, high-fidelity simulators, test track studies, road tests, and field trials [10], [14].

IV. OPPORTUNITIES

In reviewing and synthesizing the literature, we see recurring themes for positive impact. In this section, we consider opportunities in support interactions with AR, using examples related to driver' primary, secondary, and tertiary tasks (Fig. 4).

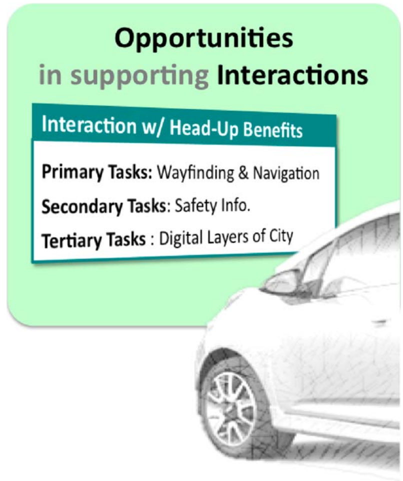

Fig. 4. ***We frame the interaction opportunities for AR automotive applications by the types of tasks the AR system supports: including general task interaction benefits (applying to all tasks), as well as benefits that apply specifically to primary, secondary, and tertiary driving tasks.***

A. Head-Up Benefits of AR on the Windshield

The most obvious benefit of AR HUDs is the ability for information to be presented and perceived without forcing drivers to look down. Since the info is presented in the driver's direct line of sight, and is overlaid on the objects it is referring to, drivers do not have to shift attention away from the driving scene, gaze is not distracted, and drivers do not need to change focus and accommodation as much when compared to traditional automotive displays. Long eyes-off-road time is known to increase crash risk, so we expect AR to benefit drivers by allowing them to keep their head up when viewing information; essentially leveraging the same head-up safety benefits that have been documented for expected events in aviation tasks [15].

Moreover, the spatial proximity of augmenting graphics relative to the real-world visual cues needed for the primary task can help reduce divided attention; especially in cases where graphics are tightly registered and perceived with corresponding real-world objects. AR applications presenting world-fixed information can further benefit drivers by cueing their attention to relevant objects, such as hazards or wayfinding landmarks. For example, BMW has developed a prototype AR windshield that overlays cues to explicitly indicate upcoming turns, and distance to next turn onto the external environment, so that the navigation information is displayed at exactly the right time and position on the driver's view of the road scene (Fig. 5).

B. Wayfinding and Navigation Aids

Driving requires both global awareness and local guidance [11]. Global awareness pertains to overall knowledge and strategies regarding the route to the destination, whereas local guidance includes tasks to control the vehicle and maintain proximal situation awareness. Since driving is the primary task, many automotive AR research

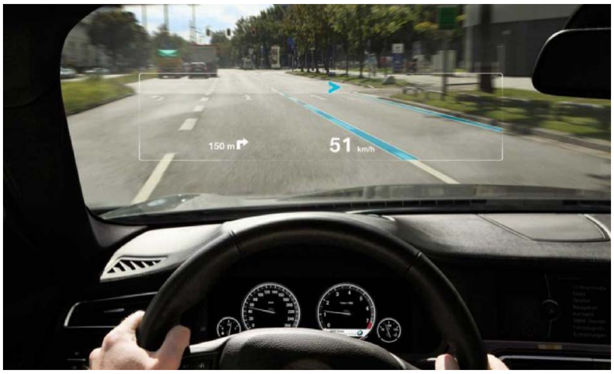

Fig. 5. ***BMW's world-fixed optical see-through windshield affords a heads-up view of information related to the primary task of wayfinding [6].***

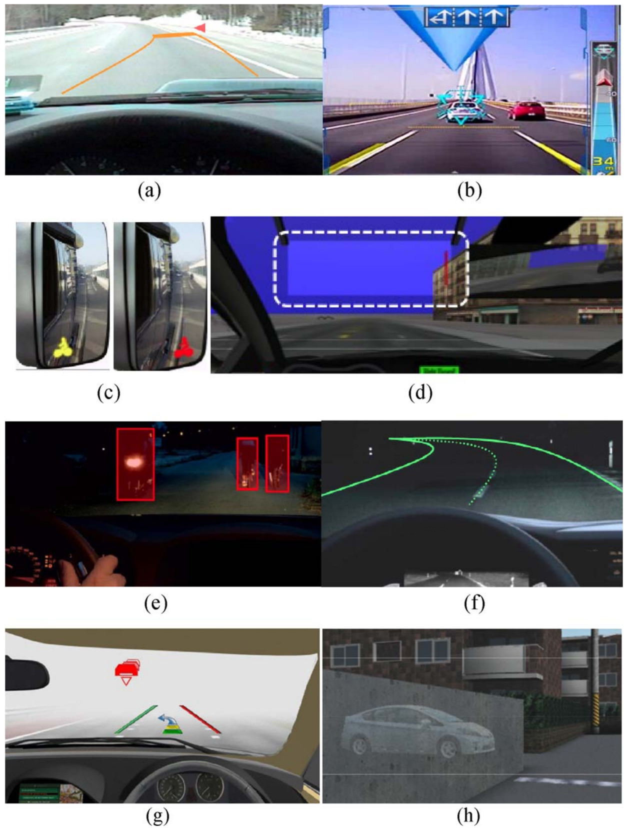

Fig. 7. ***There are many opportunities for AR to enhance existing and emerging active safety systems including: (a) braking distance indicators for forward collision warning and lane markings for lane departure warning [4]; (b) high-lighting forward vehicles for forward collision warning and following distance indictors [8]; (c) color-coded icons for side blind zone alerts [20]; (d) variable transparency cues for both side blind zone alerts and forward collision warning [19]; (e) pedestrian and (f) lane markings for lane drift warnings in low-visibility settings [22]; (g) icons cueing other vehicles and lane departure warnings [21]; and (h) X-ray vision to increase situational awareness at urban intersections [51].***

efforts to date have focused on applications for wayfinding and as a navigation aid. For example, researchers have illustrated the benefits of AR over standard map-based GPS for wayfinding with improved local guidance using video see-through device displays [16], [17], as well as optical see-through HUDs [5], [18].

Among the metaphors studied for navigation, three classes for conveying navigation information emerge (Fig. 6): world-fixed on the road; ego-centric perspective rendered above the road (in the air) [8]; and a hybrid view that depicts an ego-centric world-fixed view on the road connected to an exo-centric, top–down map perspective rendered above the road [18]. The hybrid view employs a 2.5-dimensional metaphor that provides both global awareness and local guidance simultaneously.

C. Driver Safety Information and Cues

AR applications also have the opportunity to enhance the capabilities of currently available active safety systems (Fig. 7) by, for example, augmenting and assisting critical secondary tasks (e.g., changing lanes). Specifically, AR can augment active safety systems that are designed to help prevent a vehicle accident (e.g., blind zone alerts), as opposed to passive safety systems that aim to reduce injuries obtained during crash (e.g., air bags and seat belts).

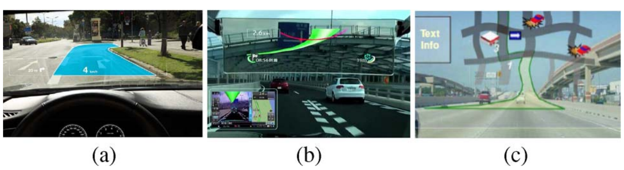

Fig. 6. ***Three metaphors for overlaying wayfinding information onto a driver's view: (a) first person, world-fixed [6]; (b) first person perspective, presented above the road to minimize occlusion of primary task [8]; and (c) hybrid view that fuses first person, world-fixed cues with top–down map view [18].***

There are a handful of opportunities for AR in active safety systems related to the longitudinal and lateral control of the car. AR visual cues can benefit longitudinal active control aid systems such as forward collision warning (FCW) [4], [19], adaptive cruise control (ACC), following distance indication (FDI) [8], and rear cross traffic alert (RCTA). Lateral control aid systems can also benefit from AR, including side blind zone alert (SBZA) [19], [20], lane change warning (LCW) [8], and lane drift warning (LDW) [21].

Sensor-driven world-fixed graphics can also be used to cue drivers' attention to relevant hazards quickly and accurately, especially for low-visibility or near-invisible objects by super imposing virtual representations of pedestrians, occluded vehicles, and driving lanes. In addition, AR can be used to assist elderly drivers' with visual and cognitive impairments in driving environments associated with increased crash risks [9], [18], [22].

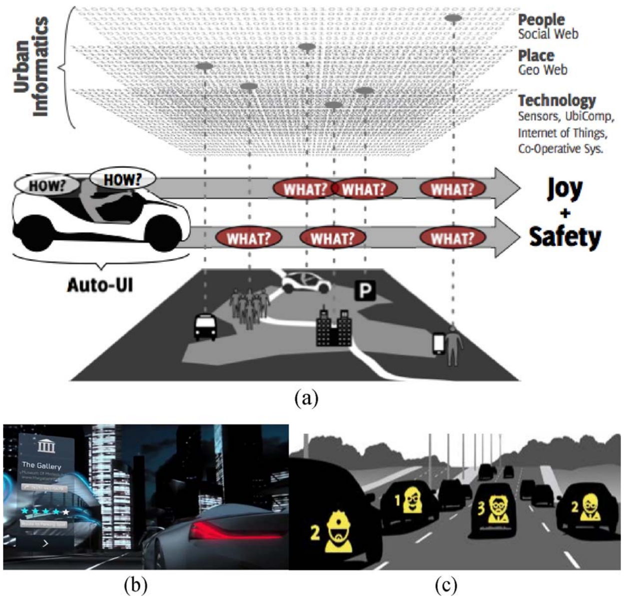

Fig. 8. ***AR developers may leverage the existing sources of geo-tagged data to create digital layers of the city in support of tertiary tasks. (a) The digital city and its three layers of data available to automotive UIs [23]. (b) The geo car—an example of a "place" layer [6]. (c) The social car concept that embodies the "people" layer [23].***

D. Digital Layers of the City

Another untapped opportunity of AR application in the automotive domain is the utilization of emerging digital city layers (Fig. 8). Urban informatics and automotive user interface communities imagine leveraging currently available geo-tagged spatial information layers that relate people (social web), place (geo-web), and technology to create new mobile experiences in vehicle [23]. These digital layers of the city have the potential to offer drivers (and passengers) a fourth dimension of information and customized views of the city that are "important to me." The *place* layer [Fig. 8(b)] can be shown via HUD and has been partially implemented in a commercial product [8]. The *people* layer has been explored through the social car concept [23] [Fig. 8(c)]. A related user study using a driving simulator with HUD suggests that lowering the anonymity and isolation of nearby drivers by revealing relationships and common interests (e.g., via AR) will reduce aggressive driving behavior [24].

V. CHALLENGES

As noted anecdotally and quantified through targeted user studies, AR displays, and particularly optical see-through head-mounted displays, are notoriously challenging to use in outdoor environments due to a host of issues. In this section, we focus on a few critical challenges related to perception and attention (Fig. 9) that are particularly applicable to the automotive domain.

Fig. 9. ***Understanding how driver perception and attention are effected by AR displays is critical in designing usable AR automotive applications.***

A. Tracking and Registration

In order to register world-fixed graphics to real-world objects, the AR system must employ some form of accurate tracking. The AR community has made great strides in improving the quality of tracking in both indoor and outdoor environments, developing methods that rely on optical, magnetic, inertial, acoustic, and ultrasonic sensors. It is beyond the scope of this paper to provide a thorough review of tracking approaches (see [25] for a recent survey); instead we provide a brief discussion of tracking issues directly related to perception in automotive applications.

In automotive AR, we can consider tracking *at least* a three-part problem: 1) determine the absolute position and orientation of the vehicle; 2) determine the relative position of the driver's head/eyes within the vehicle; and 3) identify and track objects (e.g., other cars, pedestrians, hazards) outside the vehicle. Tracking the driver's head within a moving vehicle is a technical challenge that will likely require the integration of several technologies [26] (Fig. 10).

Even with accurate tracking technology, there will inevitably be noise in the system created by, for example, vibrations from road surfaces. Few studies to date have addressed noise in automotive tracking system and its affect on drivers' perception and performance. We do not know, for example, how much noise is tolerable before drivers are not able to reliably associate a world-fixed graphic to its real-world counterpart. Certainly some amount of noise can be tolerated, but how much?

There has been some empirical work to examine the registration problem caused by car vibration. Tasaki *et al.* [27] described a method that hides the virtual object when large vibrations are detected (using an acceleration sensor). This work suggests that drivers are able to interpolate the position and orientation of (purposefully) hidden AR graphics based on the flow of AR images rendered before

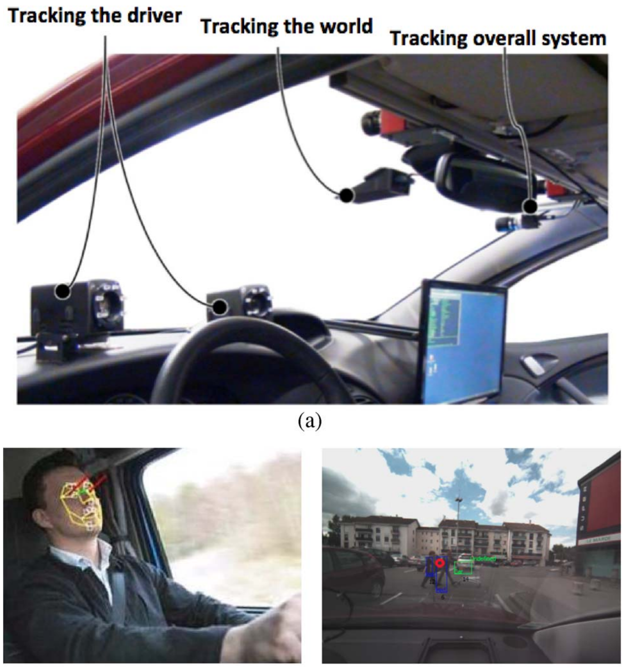

Fig. 10. ***(a) The driver-compartment components of a vision-based tracking system for automotive AR applications [26]. Using cameras and GPS, the system aims to track both (b) the driver's head and eyes, as well as (c) objects and hazards in front of the vehicle.***

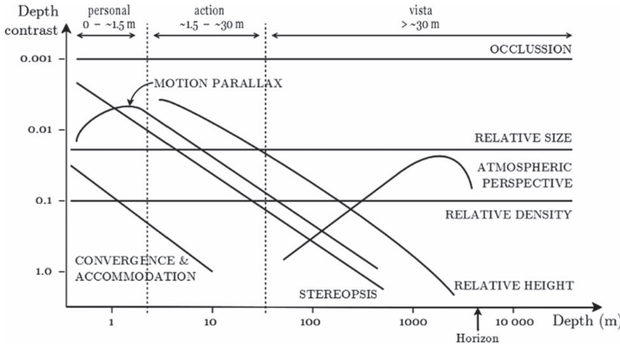

Fig. 11. ***Cutting and Vishton [28] characterize the effectiveness of monoscopic and stereoscopic depth perception cues across three spaces: personal, action, and vista. Based on this work, there are an abundance of monocular depth cues available for automotive AR applications.***

the car vibrates (and images are hidden). Further work to refine solutions for tracking and registration within vehicles is needed before we can expect widespread commercial adoption and use of AR applications in transportation.

B. Depth Perception and Estimation

Much of the existing work to date on depth perception can be applied to automotive domain to ensure a usable system. Nonetheless, there are still open questions with respect to optimal design to support driver performance for AR-based displays.

A common misconception outside the AR/VR research community is that 3-D, stereoscopic displays are somehow inherently better than monoscopic displays. One way to examine this question is to ask, how important are stereoscopic depth cues for accurately perceiving world-fixed graphics in driving applications? If it is determined that we need stereoscopic depth cues for safe and effective driving, then we need stereoscopic AR displays.

Cutting and Vishton [28] classify a large set of both monoscopic and stereoscopic depth perception cues according to the distance between the eye and the target object, dividing the visual space into three regions: personal space (0 to ∼1.5 m), action space (∼1.5 to ∼30 m), and vista space (beyond ∼30 m). They present depth-threshold functions for both monoscopic and stereoscopic depth cues (Fig. 11). Of note is that most of the strongest depth cues for objects farther than 30 m away are monoscopic (e.g., occlusion, relative size, height in the visual field, motion parallax), and a handful of these same monoscopic cues are very effective between 1.5 and 30 m as well. Since many of the world-fixed cues associated with driving tasks are beyond the physical boundary of the vehicle (i.e., the front bumper), it can be argued that monoscopic cues, and thus monoscopic AR displays, may be sufficient for automotive applications. Of course, further studies are needed to identify driver performance and interface design tradeoffs.

Conversely, if the community determines that stereoscopic depth cues are needed for driving applications, how might we deliver separate left and right images to drivers' eyes? Traditional approaches for delivering stereoscopic images (e.g., glasses) are likely ill-suited for driving. Takaki *et al.* [29] present an auto-stereoscopic, super multiview windshield display that supports accurate motion parallax at long ranges (i.e., in vista space). However, at this time, it is not clear if the extra cost needed to support stereoscopic cues at driving distances is worth the perceptual gain.

A handful of AR-specific studies that examine depth perception in action space have been published to date, including [30]–[32]. Most of this work is based on a physical action performed by the user, requiring the user to perceive distances for both the target and the object in which the user manipulates. Since we can expect some immediate driving cues to be world fixed within 30 m, the findings from these studies may apply. Specifically, AR users generally underestimate distances in action space and AR application developers and designers should account for this underestimation (e.g., via an expected window of depth estimation error) when presenting cues in action space.

C. Focus Distance to AR Graphics

While it is entertaining to consider an AR display system that provides accurate depth cues and separate focus

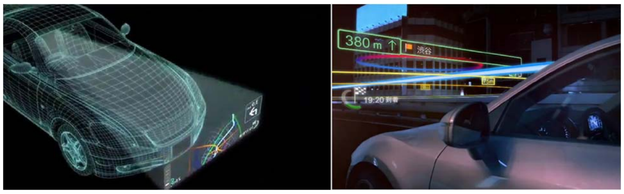

Fig. 12. *In general, AR graphics are rendered on a 2-D image plane that requires users to focus at a fixed depth. The effect of mismatches between the focus distance to the 2-D image plane and to real-world driving hazards is a concern that merits further study. Images from [8].*

distances to each visual element in the scene, the reality is that for the time being, all visual elements presented to AR users fall on a single 2-D image plane which is optically rendered at some distance at which users must focus (Fig. 12). This focus distance is directly related to focal length of the display optics, and for most of the early AR and VR HMDs, the standard focus distance was 2.0 m.

Similarly, the automotive community generally recommends a focus distance between 2.0 and 2.5 m. This may be close to the driver's resting focus (2–3 m) and is based on empirical studies about the effect of image distance on the extraction of information from the display. Even though an AR windshield display can reduce accommodation time as compared to a conventional instrument panel, drivers still need to shift focus between virtual objects on the AR display and real objects in the scene. If the focus distance to AR graphics is 2 m (near the front edge of the car), then drivers' eyes will be focused at a distance closer than objects of actual concern and potential threat. This mismatch between focusing on AR graphics as opposed to focusing on real-world objects is a significant safety concern for driving tasks. Tufano [33] describes automotive focus depth issues in greater detail, and adds, "the perceptual effects of automotive HUDs are likely to be greater than aviation HUDs."

Using AR displays with more appropriate focus depths will still require drivers to shift focus to different depths as they focus from the AR display to the scene (and back). We have seen little study to date on effects of switching focal contexts in AR specifically. Future studies on this topic should include visual tasks that require tight, concurrent visual integration between the AR graphics and the real world to fully examine the effects of shifting focus. One such study is presented in [34], where a variable focal length display was used to systematically vary the focus depth of AR images. The study found that switching focus between AR and the real world is extremely difficult when information is displayed at optical infinity (and real-world objects exist in action space). Weintraub [35] found other problems in collimated HUDs, noting that in aviation studies using collimated displays, real-world objects appeared smaller and more distant.

D. Lighting, Backgrounds, and Color Blending

Optical see-through displays present unique color perception challenges associated with the fact that a user's view is created from an optical combination, or blending of, real-world light (e.g., reflected from road scene) and synthetic colored light (i.e., the AR graphics). This interaction between real-world and synthetic light has been informally noted in various outdoor AR work, most often referring to situations where the AR graphics are washed out or difficult to see and read [36]–[40]. The color blending problem is especially challenging in automotive-based AR applications, since the lighting conditions will vary greatly from a bright sunlit day to nighttime driving. Similarly, there will be high variability in the visual complexity and spectral power distribution of real-world backgrounds as drivers move from relatively static rural scenes to highly dynamic and visually rich city environments.

Gabbard *et al.* [41] describe the color blending problem of a typical outdoor AR usage scenario (Fig. 13, top), noting several inputs that determine the color of light that reaches a user's eye such as the ambient light source(s), nature of the real-world background material, desired AR color, as well as display- and GPU-dependent characteristics.

The interaction of backgrounds and natural lighting can affect the usability of AR graphics (e.g., text legibility), a phenomenon that has been measured in studies such as [42] and [43]. If the AR color is impacted by dynamically changing lighting and background conditions, how can automotive AR designers ensure that visual cue color is perceived correctly? This is especially critical in situations where colors have intended an important meaning. Color is highly contextual, and thus knowledge of backgrounds and surrounding visual field, as is available in video-based AR systems, can be extremely helpful in selecting colors to ensure discriminability.

One proposed approach uses active, or adaptive AR user interfaces, that sample the background scene behind the AR graphics, as well as the ambient lighting to adjust the system accordingly with the goal of ensuring consistent color, contrast, and improved visual acuity [37]. An alternative solution is often framed as simply needing brighter outdoor AR displays, however a recent engineering measurement study has shown that there are chromaticity components (independent of luminance components) effected by color blending [44], suggesting that brighter displays may not singularly solve this problem (although brighter displays are certainly welcome). This study measured the color of light as it exits the HMD by varying 27 AR colors presented over 11 real-world backgrounds. By comparing the blended color created from a single AR color on a given background to the blended color created by the same AR color on a second background, the authors identified four categories of color shifting phenomenon: washout due to chromaticity, washout mostly due to luminance, washout due to both chromaticity and luminance, and linear shift in chromaticity (Fig. 13, bottom).

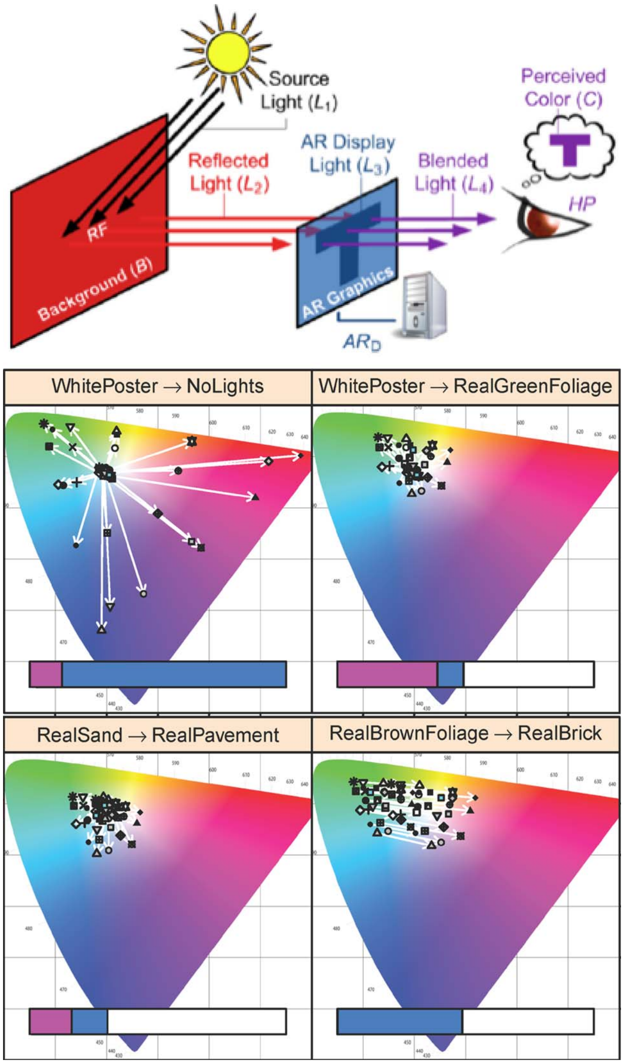

Fig. 13. ***(Top) Transportation AR designers that employ optical see-through displays will need to consider the color perception issues created from the optical blending of color light from both background and AR graphics' sources [41]. (Bottom) Four examples of color blending as measured in [44], depicting how each of 27 AR colors are affected when the real-world background changes. Note that the horizontal stacked bar charts denote total perceptual change depicting both luminance (purple) and chrominance (blue) components.***

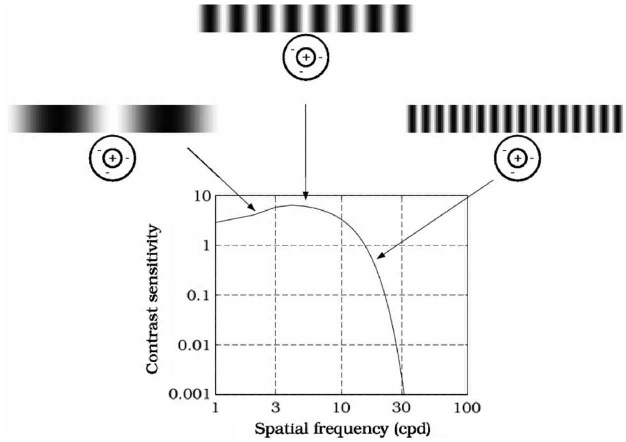

Fig. 14. ***AR graphics are susceptible to contrast sensitivity, whereas the amount of contrast needed to detect a graphical element is dependent upon the spatial frequency of the graphic as well as the amount of contrast present between the graphical element and the real-world background. Our ability to ensure high visual acuity in transportation of AR applications is difficult since the contrast is continuously altered by dynamic lighting and background conditions.***

E. Visual Acuity and Contrast

The color blending nature of optical see-through displays introduces a related challenge for automotive AR; namely, the fact that changing AR colors affects the contrast between graphics and the real world, and as such has an effect on contrast sensitivity and visual acuity. Visual acuity, simply put, is the ability to see fine details, and is highly dependent upon contrast. In general, the better is the contrast, the better the acuity. This oversimplification may suggest that a drivers' ability to recognize objects or read AR text is only a function of the AR graphics contrast. However, the drivers' ability to quickly perceive and recognize AR graphics is a function of both graphic size and contrast.

Studies have examined the relationship between size and contrast by varying contrast and identifying the smallest stimulus that a user can identify at a given contrast. Contrast sensitivity is often measured by detecting the threshold of contrast required to accurately perceive the target. Contrast sensitivity curves have been studied in AR, and show that different displays have different curves, and that targets with lower spatial frequency require less contrast to detect [45].

As a general rule of thumb, a greater amount of contrast is needed for both low and high spatial frequencies, while less contrast is needed for spatial frequencies in between (Fig. 14). In design of AR applications for automobiles, it is important that users are able to see the overall shapes of all differently sized objects (cars, trucks etc.) with a varying level of detail and spatial frequency (e.g., writing on signposts). Thus, in a driving scenario, it is important to know if all these differently sized objects become just visible (just above threshold) at the same contrast or whether differently sized objects require different amounts of contrast to be just visible.

F. Driver Distraction

Distracted driving may be as old as the horse and buggy time, with today's challenges coming from a multitude of both personal and in-vehicle technologies. Distractions can be from electronic devices, such as navigation systems and cell phones, or more conventional distractions such as interacting with passengers and eating. In 2011 alone, over 3000 people were killed and an estimated 387 000 were injured in distracted driving crashes. Moreover, 10% of all 2011 fatal crashes were reported as distraction related [46]. Distracted driving is generally defined as an activity that diverts a driver's attention away from the primary (driving) task, and includes manual distractions (taking hands off the wheel), visual distractions (taking eyes off the road), and cognitive distractions (taking your mind off driving). Young and Regan [47] provide a thorough review of the literature on in-vehicle issues related to distracted driving. Moving forward, we can expect AR applications to have the potential to trigger all three types of distractions, as users must visually attend to AR information, think about what that information may mean (especially for nonprimary task information), and potentially interact with that information via manual controls (e.g., buttons on a steering wheel).

According to a study of driver distraction in commercial motor vehicle operations by the Virginia Tech Transportation Institute, 71% of crashes and 46% of near-crash events (as sampled from 4452 safety-critical events over 12 weeks) were due in part to drivers engaging in nondriving related tasks [48]. When drivers perform highly complex secondary and tertiary tasks while driving, there is a significant increase in risk. The study also examined eye movement data, quantifying the association between increased risk and longer eyes-off-forward-road times, suggesting that drivers (and AR designers) avoid tasks that require drivers to look away from the forward roadway. While this work suggests there are opportunities for head-up automotive AR applications, similar studies are needed to quantify the effects of visual and cognitive distractions associated with overlaid AR information.

The National Highway Traffic Safety Administration has published *Visual Distraction Guidelines* aimed at manufacturers and designers of in-vehicle electronic systems [49]. How do these established guidelines apply to AR displays? How does a virtual object interfere with the perception of the main driving environment? Where should we place virtual objects (especially screen-fixed objects) on windshield to keep drivers' attention forward, yet minimize occlusion and crash threats? These guidelines can serve as a starting point for automotive AR researchers, to verify and extend as needed.

G. Clutter and Occlusion

If too many AR elements are presented, or if AR elements are presented in an *ad hoc* manner, the resulting real-world view can be cluttered, potentially obscuring the driver's view of objects and hazards. Even a minimal graphic on a screen-fixed HMD can block objects when a driver turns or tilts his/her head (Fig. 15). As such, we recommend that AR application designers be extremely parsimonious with information presented via AR, showing the most appropriate information for a given driving context.

There has been some research to address the problem of clutter in outdoor AR. For example, Bell *et al.* [50] describe a dynamic layout strategy that could be used for AR information that is not stringently world fixed, but needs to be associated with real-world objects (e.g., labels). This approach modifies the AR graphic's size, position, and transparency to generate an optical placement of the AR graphics with the aim of maintaining spatial proximity when needed, yet minimize occlusion. An empirical study that examined the level of detail needed to effectively aid drivers in estimating collisions suggests that a simple, symbolic representation of the occluded vehicle may be sufficient for collision avoidance tasks [51].

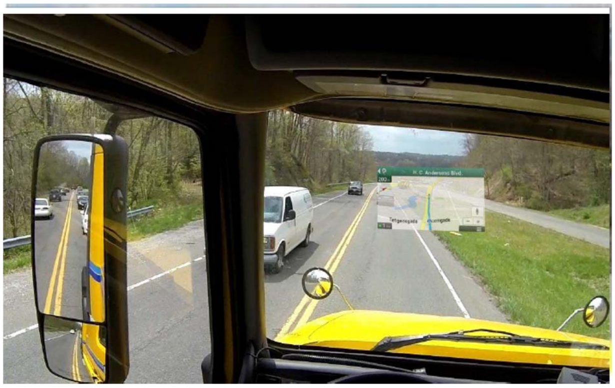

Fig. 15. ***Even an uncluttered AR scene can accidentally occlude important real-world visual cues.***

Occlusion is a separate, yet related concern; with at least two aspects to consider. First, if we wish to render AR graphics that are critical to the primary task, but are occluded by either real or other virtual objects, we must develop intuitive means of visually presenting that information such that drivers can accurately perceive the occluded object's position in depth. For example, assuming a vehicle-to-vehicle infrastructure in place, we can imagine an interstate driving scenario where a slow-traveling disabled vehicle is positioned within a line of three or more large commercial tractor trailers, and our driver is in the rear of this line. Optimally, the AR display will visually cue this occluded hazard in such a way that the driver can easily infer the ordinal position of the disabled vehicle (e.g., in front of the second tractor trailer as opposed to the third). Livingston *et al.* [52] describe a study that examined multiple methods for visually depicting occlusion in outdoor AR, varying opacity, stroke, and fill settings. The study found that users have difficulty discerning more than a few levels of occluded objects, even though AR graphics' opacity appears to be promising as an effective layering and ordering cue.

Second, we know that occlusion is the most dominant depth cue regardless of distance between the driver and the object. Therefore, AR graphics should ensure that occlusion-based depth cues are not reversed. Drivers may be easily confused if AR graphics are rendered without

Fig. 16. ***Since occlusion is the most dominant depth cue, care must be taken to avoid confusion in depth between real-world objects and AR graphics [17].***

attention to this detail. If applicable, image tracking of real-world objects (such as the truck shown in Fig. 16) should be used so that AR graphics can be culled accordingly.

H. Over-Reliance and Trust

While it would be convenient to assume that drivers can attend to both AR graphics and the real-world simultaneously, previous research suggests that we cannot effectively process separate information channels simultaneously [53], [54]. Instead we switch our attention back and forth, cognitively multitasking in today's vernacular. In some cases, one channel will capture, or dominate, our attention. Gish and Staplin [55] provide a review of this phenomenon in various HUDs, and suggest that AR displays for automobiles are likely to capture our attention (away from the driving scene) in moments of high driver workload and temporal uncertainty.

In a similar manner, drivers may become reliant on the AR channel, and fail to switch attention to important real-world cues when needed. For example, when a visual cue (e.g., an AR graphic pointing to the location of a driver's next turn) is presented in support of a wayfinding task, drivers may immediately attend to that cue at the expense of other (non AR-cued) important real-world cues, such as nearby vehicle or pedestrian [56].

Wickens *et al.* [57] describe attention and trust biases that are applicable to AR for driving tasks. In this context, we can expect there to be instances where drivers put too much trust in the AR information, and ignore other critical, sometimes conflicting, real-world information. Conversely, we can expect other scenarios where drivers ignore the information presented via AR systems when it is in their interest to attend to it, perhaps due to previous experiences where information was inaccurate (i.e., the driver does not trust the system any longer).

VI. CONCLUSION

Bona fide automotive AR application is near a tipping point. The infrastructure needed to create, synthesize, and route meaningful geolocated data to our vehicles is already here. Usable AR display technology is already in vehicle in the form of video-based backup assist AR, and recent investments in windshield-based optical see-through displays may enable commercially available systems within the next few years. The most successful automotive AR applications will take into consideration a wide range of perceptual and visual attention issues within the driving context. We present some of these issues based on our experiences with mobile, outdoor, head-mounted optical see-through displays. However, much more research is needed to ensure safe, reliable AR applications for transportation. ■

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