Augmented Reality Pedestrian Collision Warning:
An Ecological Approach to Driver Interface Design and Evaluation

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Abstract

Augmented reality (AR) has the potential to fundamentally change the way we interact with information. Direct perception of computer generated graphics atop physical reality can afford hands-free access to contextual information on the fly. However, as users must interact with both digital and physical information simultaneously, yesterday's approaches to interface design may not be sufficient to support the new way of interaction. Furthermore, the impacts of this novel technology on user experience and performance are not yet fully understood.

Driving is one of many promising tasks that can benefit from AR, where conformal graphics strategically placed in the real-world can accurately guide drivers' attention to critical environmental elements. The ultimate purpose of this study is to reduce pedestrian accidents through design of driver interfaces that take advantage of AR head-up displays (HUD). For this purpose, this work aimed to (1) identify information requirements for pedestrian collision warning, (2) design AR driver interfaces, and (3) quantify effects of AR interfaces on driver performance and experience.

Considering the dynamic nature of human-environment interaction in AR-supported driving, we took an ecological approach for interface design and evaluation, appreciating not only the user but also the environment. The requirement analysis examined environmental constraints imposed on the driver's behavior, interface design translated those behavior-shaping constraints into perceptual forms of interface elements, and usability evaluations utilized naturalistic driving scenarios and tasks for better ecological validity.

A novel AR driver interface for pedestrian collision warning, the virtual shadow, was proposed taking advantage of optical see-through HUDs. A series of usability evaluations in both a driving simulator and on an actual roadway showed that virtual shadow interface outperformed current pedestrian collision warning interfaces in guiding driver attention, increasing situation awareness, and improving task performance. Thus, this work has demonstrated the opportunity of incorporating an ecological approach into user interface design and evaluation for AR driving applications. This research provides both basic and practical contributions in human factors and AR by (1) providing empirical evidence furthering knowledge about driver experience and performance in AR, and, (2) extending traditional usability engineering methods for automotive AR interface design and evaluation.

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General Audience Abstract

On average, a pedestrian was killed every 2 hours and injured every 8 minutes on U.S. roadways in 2013. Most common driver errors responsible for pedestrian collisions were drivers' lack of situation awareness due to low visibility or unexpected appearance of pedestrians. As a solution to the problem, automakers introduced pedestrian collision warnings, taking advantage of recent advances in sensor technology and pedestrian detection algorithms. Once pedestrians are detected in the vehicle's path, warnings are given to the driver typically through auditory alarms and/or simple visual symbols. However, with current warnings that often lack spatial information, drivers need to further localize and evaluate approaching pedestrians' movement for appropriate decision and reaction. Augmented reality (AR) is one of the most promising solutions to address the limitations of current warning interfaces. By overlaying computer generated conformal graphics atop physical reality, AR head up displays (HUDs) can guide drivers' attention to dangerous pedestrians, affording direct perception of spatial information about those pedestrians.

The ultimate purpose of this work is to reduce pedestrian accidents by design of driver interfaces, taking advantage of AR HUDs. For this purpose, we aimed to (1) design a novel driver interface for cross traffic alerts, (2) prototype design ideas for a specific use-case of pedestrian collision warning, and (3) evaluate usability of the new design ideas in consideration of unique aspects of human-environment interaction with AR while driving.

We proposed a novel driver interface for pedestrian collision warning, the virtual shadow, which can cast shadows of approaching pedestrians to the vehicle's path via AR HUDs. Usability evaluations in a driving simulator and a roadway showed the potential benefits of the proposed idea over existing warnings in driver attention management, situation awareness, task performance with reduced workload. Thus, this work demonstrated the capabilities of AR HUDs as intuitive and effective interfaces for vehicle drivers.

To my wife, Hyunsook and my daughter, Jian

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Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Problem Statement and Motivation

The problem. On U.S. roadways, 4,735 pedestrians were killed and an estimated 71,000 were injured in traffic crashes in 2013 (NHTSA, 2015a). On average, a pedestrian was killed every 2 hours and injured every 8 minutes. Pedestrian deaths accounted for 14% of all traffic fatalities and the pedestrian fatality rate has increased (11% in 2007) while the total number of fatalities has decreased (NHTSA, 2015b). The pedestrian fatality rates of major cities are significantly higher than the national average (e.g., 60.8% of traffic fatality was pedestrians in New York City in 2013). Even worse, pedestrians are the most vulnerable road users since they do not have any protective equipment such as airbags or safety belts. About 25% of pedestrians involved in traffic accidents were killed or incapacitated (KI) which is significantly higher than 6.9% KI rate of vehicle occupants (NHTSA, 2015a, p. 106). A report on contributing factors to pedestrian fatality (NHTSA, 2015a, p. 151) suggests that drivers failed to appropriately detect pedestrians due to low visibility (15.5% such as dark clothing and no lighting) or unexpected appearance of pedestrians (adding up to 47% including improper crossing, standing, working and wrong-way walking).

Current solutions and limitations. As one of the solutions to the problem, automakers introduced pedestrian collision warnings, taking advantage of recent advances in sensor technology and pedestrian detection algorithms (Benenson, Omran, Hosang, & Schiele, 2014). Once pedestrians are detected in the vehicle's path, warnings are given to the driver typically through auditory alarms and/or simple visual symbols (e.g., Mobileye, 2015). However, notifying drivers of the presence of impending hazards may not be sufficient to solve the problem. The 2014 annual report on road casualties in Great Britain (Lloyd, Wilson, Mais, Deda, & Bhagat, 2015, p. 47) reveals that drivers' failure to look properly (46%) and failure to judge other person's path or speed (24%) were the most common contributory factors in road accidents. However, with current warnings that often lack spatial information, drivers need to further localize (i.e., recognize direction and distance of) and evaluate approaching pedestrians' movement for appropriate decision and reaction.

Opportunities and challenges of augmented reality. Augmented reality (AR) is one of the most promising solutions to address the limitations of current warning interfaces. By overlaying computer generated conformal graphics atop physical reality, AR head up displays (HUDs) afford direct perception of spatial information about dangerous pedestrians. However, the effects of this novel technology on driver performance and experience is not yet fully understood. Moreover, AR compels users to interact with not only information on the display but also environmental changes, and new AR technology may require a new approach to interface design and evaluation.

1.2 Research Purpose, Objectives and Questions

The ultimate purpose of this study is to reduce pedestrian accidents by design of driver interfaces, taking advantage of AR HUDs. For this purpose, this work aims to (1) identify information requirements for pedestrian collision warning, (2) design AR driver interfaces, and (3) quantify effects of AR interfaces on driver performance and experience. Along the course of interface development, this work will also examine human factors research questions relevant to each objective.

Objective 1: Identify information requirements

- Research Question (RQ1): What are the work demands of automobile driving (constraints that shape the driver's behavior)?
- Research Question (RQ2): What information should be available for the driver to avoid pedestrian collision (content and structure of information)?

Objective 2: Design AR driver interface

- Research Question (RQ3): How should critical information regarding pedestrian collision avoidance be presented to the driver (perceptual forms of interface elements)?

Objective 3: Quantify effects of AR interfaces on driver performance and experience

- Research Question (RQ4): Do AR pedestrian collision warnings have the potential to improve the quality of driver information processing?
- Research Question (RQ5): What are the effects of AR pedestrian collision warnings on driver situation awareness and workload?

- Research Question (RQ6): What are the effects of AR pedestrian collision warnings on driver behavior and performance?

1.3 Method Overview

Driver vehicle interface design has a unique challenge; drivers need to simultaneously interact with both information on the display and environmental changes in physical world. However, traditional user-centered design (UCD) approaches that focus on human-computer interaction may not always adequately address the dynamic nature of environmental changes behind the display. This work appreciates the triadic nature of interface design (human-environment interaction mediated by interface) and follow an ***ecological approach*** (Figure 1.1). The interface design should start from examining the work environment (physical and social reality of the work domain) and end by examining the user (cognitive process, mental models, strategies and preferences), especially when the user's goal-directed behaviors are highly affected by dynamic environmental constraints (Vicente, 1999). Throughout the entire interface development life cycle (analysis, design and evaluation), this work deliberately appreciated not only "the user" but also "the work ecology – underlying physical and functional mechanism of the work domain".

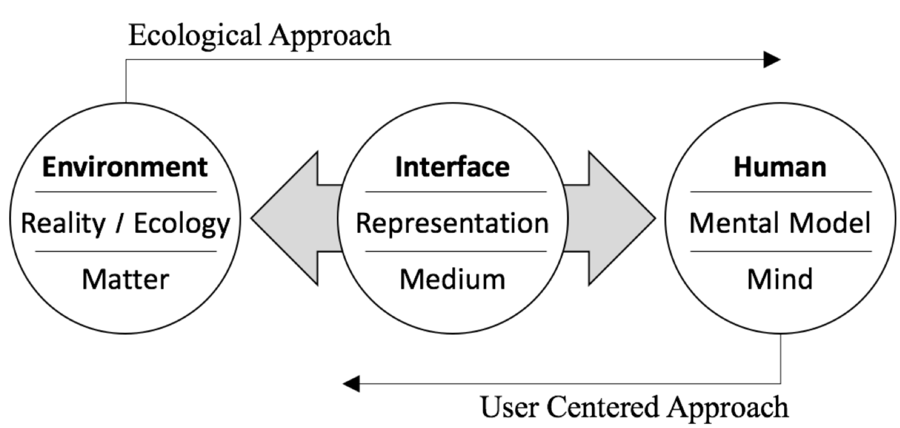

Figure 1.1 The triadic view on interface design.
Human performance and experience are considered as results of interaction between matter and mind via medium. (Adpated from Bennett & Flach, 2011, p. 18; Flach, 2015; Vicente, 1999, p. 48)

1.3.1 Identify Information Requirements (methods to answer RQ1 and 2)

This work first analyzed environmental constraints that shape the driver's behavior. *Work domain analysis* (WDA, Vicente, 1999, p. 149) captured the physical and functional mechanism of the automobile driving for safe transportation. As a result of WDA, we were able to identify information content (work domain variables) and structure (relationships among variables) to be available for safe transportation in any situation to any driver. Next, this work further explored the driver's cognitive process in cross traffic situations. *Control task analysis* (CTA, Vicente, 1999, p. 181) identified cognitive constraints (required cognitive activities) and information needs for the driver to avoid collision with pedestrians.

1.3.2 Design AR Driver Interface (methods to answer RQ3)

Ecological interface design (EID) approach inspired us to design a driver interface that is compatible with both the physical reality of driving and the characteristics of the driver's cognitive process. EID is a methodology for interface design that makes deep structure of a work domain salient to leverage people's various capabilities for information processing (Bennett & Flach, 2011, pp. 103-104). To determine specific forms of interface elements, we leveraged the benefit of both design *metaphor* and *analogy* (Bennett & Flach, 2011, pp. 120-122). Abstract geometric shapes were used to configure an emergent feature that represents the dynamics of cross traffic (analogy). We also leveraged people's experience by designing an emergent feature that looks similar to a familiar object in their everyday life (metaphor).

1.3.3 Quantify Effects of AR Driver Interfaces (methods to answer RQ4, 5 and 6)

As explicit efforts to respect the ecological validity of the study, we actively employed (1) *naturalistic driving scenarios* and develop (2) *realistic tasks* for our participants throughout all usability evaluations. This work also utilized (3) *a combination of evaluation methods and experimental settings* that complement each other with unique, applicable task demands of driving and driver experience measures to best answer each research question.

Analytic usability evaluation (RQ4). At the early stage of usability evaluation, we wanted to validate new design concepts with rapid prototypes before empirical evaluations with high fidelity prototypes. Therefore, we conducted a *heuristic walkthrough* (Sears, 1997) in a driving simulator where *expert evaluators* mimicked driving while watching pre-recorded driving video footage, and predicted quality of the driver information processing as well as usability problems. Design ideas were prototyped by *augmented video technique* that overlaid computer generated graphics atop driving video footage (Soro, Rakotonirainy, Schroeter, & Wollstdter, 2014). A set of heuristics was developed and given to help the experts predict driver performance in sensation, attention management, situation awareness, and decision-making.

Empirical usability evaluation in a driving simulator (RQ5). In this user study, we focused on cognitive measures of driver experience (e.g., situation awareness, confidence and workload) rather than behavioral or performance measures. For this purpose, a *driving simulator* was used, since we could investigate the driver's cognitive process with more controls on driving scenarios and tasks without actual threats (even "virtually" dangerous) to the human subjects. We directly measured driver situation awareness by a widely accepted query-based method, *situation awareness global assessment technique* (SAGAT, Endsley, 2012) which also leverages the benefit of driving simulation. Subjective ratings on workload (NASA-TLX, Hart, 2006) and confidence in driver situation awareness were collected as well. Furthermore, results from the empirical usability evaluation (by actual users) were compared with those from the analytic usability evaluation (by usability experts).

Empirical usability evaluation in a parking lot (RQ6). In this user study, we investigated effect of AR interface on the driver's behavior and performance. We recruited actual users and let them drive a *test vehicle equipped with working prototypes* of pedestrian collision warnings in a parking lot where drivers must handle actual task demands (visual, cognitive and manual) of driving in controlled but realistic driving scenarios. Drivers' behavior and performance were monitored and recorded by various equipment such as *eye tracking glasses, in-vehicle cameras, and a global positioning system* (GPS). To be more specific, this user study examined the effects of interface (specificity of representations) and environmental factors (emergency of situation) on driver behavior (e.g., gaze and foot movement) and braking task performance (e.g., total stopping distance and peak deceleration).

2. Literature Review

2.1 Theoretical Background

Bennett and Flach (2011) argue that designing displays and interfaces is a *subtle science* and *exact art*. Interface design has scientific basis (theories informed by empirical results from research) but theories always need to be adapted to specific circumstances (i.e., subtle). It is also obvious that a good interface is a work of art but is required to convey very specific and concrete information (i.e., exact) to support users' task. Therefore, there are many different perspectives on interface design that have different strengths and contributions. In this section, we review two alternative theoretical paradigms for interface design, followed by discussion about cognitive systems engineering and ecological interface design framework that provide a conceptual basis for this study.

2.1.1 Two Alternative Views on Interface Design

The Dyadic View. Traditional *user-centered design* approaches are rooted on the dyadic paradigm that focuses on interaction between the interface and the user (Flach, 2015). According to this view, designers should develop interfaces to match the user's mental model to better support the user's needs, taking into account the capabilities and limitations of the user's internal information processes. The research interests typically lie on interaction between signifier (stimulus provided by interface) and signified (the user's perception or interpretation) in controlled environment such as experimental setups in research laboratories (Bennett & Flach, 2011). Therefore, *syntax* (perceptual forms such as size, shape, color and so forth) of interface representations and their effect on the users' perception, attention, and cognition are of interest. According to this paradigm, the meaning is constructed from ambiguous and impoverished stimuli using limited or biased human information processing. This view has significantly contributed to the conventional body of knowledge that provide fundamental basis for interface design.

The Triadic View. On the other hand, the ecological or *use-centered design* approaches are rooted on the triadic paradigm that appreciate interaction between the user and the environment mediated by the interface (Flach, 2015). According to this view, designers should develop interface representations that correspond with the work ecology and coherent with the user's mental process to facilitate skilled action within inherent external constraints imposed on the user's behavior. This view considers the meaning of information as affordances of a situation that are possibilities and consequences of the user's behavior. This view argues that the meaning (affordance) is not created by the mind but discovered by the mind. Therefore, *semantics* (content and structure) of interface and their effect on the user's cognitive process and performance in actual or representative situations are of interest (Bennett & Flach, 2011).

2.1.2 Cognitive Systems Engineering and Ecological Interface Design

As mentioned in the first chapter, this work advocates the triadic view on interface design and follows ecological approach that would better fit driver interface design. Ecological interface design framework that is based on cognitive systems engineering provided conceptual and theoretical background of the rest of this study.

Cognitive Systems Engineering (CSE) is a discipline of systems development that provides theoretical and methodological framework for the analysis, design and evaluation of complex sociotechnical systems (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). An exemplary framework from CSE that can be applied to design computer-based systems for human work is cognitive work analysis (CWA, Vicente, 1999). It is based on the concept of behavior shaping constraints and provide models of the work domain, control tasks, strategies, cooperation, and worker competencies in an integrated framework. From the interface design perspective, CWA helps identify information requirements and implications for design and evaluation of interfaces for dynamic and complex systems.

Ecological Interface Design (EID) is a more focused framework for interface design that respect interaction between the user and the environment mediated by the interface. Therefore, EID addresses two questions related to interaction among (1) the interface-environment and (2) the interface-user; (1) how to design interfaces that is compatible with the work ecology or domain complexity? and (2) how to communicate information that is compatible with human information processing? CWA provides models to answer these questions. First, work domain analysis (WDA) provides tools to model the work ecology that includes environmental constraints that shape the user's behavior. Second, control task analysis (CTA) provides tools to model the user's cognitive process that includes cognitive constraints that affect the user's behavior. Finally, skill, rule, and knowledge (SRK) taxonomy bridge the gap between (1) the work ecology and (2) the user's cognitive process by providing a model of flexible mechanisms people have for processing information and managing complexity. Based on WDA, CTA and SRK taxonomy, EID provides three general principles for user interface design that is compatible with the work ecology and can leverage people's flexible cognitive processes (Vicente, 1999, p. 295).

- To support skill-based interaction via time-space signals, workers should be able to act directly on the display
- To support rule-based behavior, provide a consistent one-to-one mapping between the work domain constraints and the cues or signs provided by the interface
- To support knowledge-based problem solving, represent the work domain in the form of an externalized and faithful model (symbols)

The ultimate goal of EID is to design interfaces that can leverage the power of lower levels (less demanding skill-based) cognitive controls while still supporting all three levels to allow users to cope with unexpected events.

2.2. Related Works

This section reviews human factors in AR displays and driver interface design by discussing human capabilities and limitations in visual attention and perception, followed by research efforts and challenges to enhance driver performance with reduced efforts via AR interface design (see Appendix A for summary of the literature review.)

2.2.1 Human Visual Attention and AR Driver Interfaces

Human Visual Attention in Driving. Driving is a demanding task that continuously requires the driver to deploy attention across the roadway and within the vehicle to select the most appropriate stimuli, focus on specific information, and divided attention to integrate them to understand current situation. However, the limited capability of human vision (field of view and depth of field) do not allow to access all required information easily.

Although humans have about 180° horizontal and 130° vertical *field of view* (Duchowski, 2007, p. 30), we need to move our head and eyes to access information (C. D. Wickens, Hollands, Banbury, & Parasuraman, 2015, p. 51) or re-focus our eyes to stimuli at different depth. Within human field of view, the useful field of view (UFOV) corresponds to the surface around the point of fixation inside which information can be perceived and processed during a visual task. According to Seya's experiment, the UFOV in driving may be asymmetric among the meridians in the visual field roughly ranging from 15° to 20° (Seya, Nakayasu, & Yagi, 2013). This capability can be degraded by aging to 11° for a 50-year-old person (Langlois, 2013).

Humans need to refocus eyes, to accommodate information at different depth. The *depth of field* (DoF) refers to the range of distances in which an object appears to be in focus without the need for a change in accommodation. Roughly, the human eye's depth of focus is estimated as 3.33~4m (i.e., 0.25 ~ 0.3 diopters, Campbell, 1957) which can be modulated by several factors. For instance, the DoF ranges from 11m to 33m for an object 17m away when the pupil diameter is 4mm (Jannick P Rolland & Fuchs, 2000). However, human eye's accommodation capability decreases with age. Inuzuka, Osumi, and Shinkai (1991) showed that the elderly's recognition time to stimuli on a HUD increases significantly given a focus distance of less than 2.5m.

Driver Attention Guidance by AR interfaces. HUDs have capability to address aforementioned limitations of human visual attention by enhancing range of visual capability and reducing effort to maintain attention across environmental elements. Therefore, relatively large amount of research efforts has been dedicated to visual attention and have showed both benefits and costs of attention guidance by AR interfaces.

AR HUDs can support diverse use-cases by guiding drivers' attention to critical environmental elements such as (1) objects difficult to see (e.g., low-visibility settings), (2) occluded objects, (3) objects out of drivers' field of view, and of course (4) additional information associated with objects in view. In a simulation study, Charissis and

Papanastasiou (2010) found that virtual representations of vehicles, lane edges, and driving directions resulted in less collisions under limited visibility conditions (e.g., fog) with sudden traffic congestion. Yasuda and Ohama (2012) enhanced drivers' attention by using x-ray vision metaphor at blind corners to reduce crossing collisions. Kim, Wu, Gabbard, and Polys (2013) has prototyped an AR driver interface that inform drivers of vehicles in the blind spots and showed faster driver reaction time to warnings than an extant interface. Tran, Bark, and Ng-Thow-Hing (2013) have designed left-turn aid interface where drivers can see predicted (3 sec) paths of oncoming vehicles for safer left turn. Some research groups have utilized rear window notification metaphor where drivers see information about a lead vehicle (e.g. time to collision, relative acceleration…) super imposed on its rear window to avoid forward collision (Saffarian, de Winter, & Happee, 2013; Wai-Tat, Gasper, & Seong-Whan, 2013).

Despite benefits of attention guidance via AR HUDs, sometimes AR graphics can capture drivers' attention and distract them from other critical elements on the road. AR graphics can be distractive due to their (1) salience, (2) frequent changes, and (3) visual clutter.

Sharfi and Shinar (2014) reported that highlighting lane markers in foggy or night driving condition have impaired drivers' pedestrian detection and reduced safety. Salience contrast between highlighted lane markers and other road elements might hinder driver's divided attention. To avoid attention capture by too salient AR graphics, Palinko et al. (2013) have tried to utilize drivers peripheral vision to guide driving direction. They prototyped a low-cost HUD replacing the sun visor (a matrix of LED illuminating to indicate the lane to take), and showed better attention behaviors (eye on the road time 94.4% vs eye on the HUD 0.5%).

Frequently changing AR graphics can capture drivers' attention as well. Wolffsohn, McBrien, Edgar, and Stout (1998) have tested drivers divided attention where drivers need to read out an AR speedometer while paying attention to brake lights of the lead vehicle. Frequently changing information on the AR HUD captured drivers' attention and caused change blindness even within their central vision. Even surprised, drivers continuously refocusing their eyes between the brake lights and the AR speedometer in spite of use of a collimated binocular HUD which does not require drivers to re-accommodate. “Show only when necessary” could be one of strategies to address this problem. Two research efforts support this strategy. Dijksterhuis, Stuiver, Mulder, Brookhuis, and de Waard (2012) tested an adaptive lane keeping support system where a AR HUD interface shows current lane position only when drivers reaction is required. A study on night-vision display showed that the display offering discontinuous support (i.e. only in critical situation) helped drivers reacted more reliably (i.e. showed less variance in reaction times; Kovordanyi, Aim, & Ohlsson, 2006). Conversely, Seppelt and Lee (2007) argued, as a result of a user study on DVIs for adaptive cruise control, that providing drivers with continuous information about the state of the automation is a promising alternative to the more common approach of providing imminent crash warnings when it fails. Therefore, the temporality of AR graphics should be carefully chosen such a way that is compatible to tasks, required data type and physical environment.

Visual clutter is one of the enemies of focused attention and selective attention. Cluttered displays require more effort to focus on specific information and reduce drivers’ attentional resources for divided attention. Among four source of clutter (numerosity, proximity, disorganization, heterogeneous), Burnett and Donkor (2012) evaluated the effect of HUD numerosity on drivers peripheral detection performance. As clutter increased, drivers’ capability of focused attention (read out HUD information), divided attention (detect obstacles in periphery) and driving performance (probability of lane departing) was deteriorated. Moreover, the clearest negative effect was found when progressing from four to seven symbols on the HUD. As a countermeasure for the clutter issue, a study that examined the level of detail of AR graphics suggested a simple symbolic representation of an occluded vehicle may be sufficient for collision avoidance (Yasuda & Ohama, 2012).

HUDs can also reduce drivers’ need for dividing their attention by integrating associated information. Typical examples are navigation aids that allow drivers not to look down to get driving directions by superimposing navigation cues to real-world landmarks. Medenica, Kun, Paek, and Palinko (2011) simulated an AR navigation aid that show ego-centric virtual cables rendered above the road to compare usability of different types of navigation aids. Over other navigation aids either a traditional map-based aid or a video see-through AR device, the AR HUD showed the best in all three measures; drivers attention behavior, driving performance and subjective rating of mental workload. With the AR HUD, drivers did not need to divide their attention to match driving direction from the device to their corresponding real world landmarks, so that drivers could save their attention resources for any other critical events on the road.

2.2.2 Human Depth Perception and AR Head-Up Displays

Human Depth Perception. Localization (direction and distance) of road hazards and landmarks is critical for drivers' appropriate reaction and safe driving. In natural viewing conditions, the human visual system estimates the 3D structure of the world by combining multiple sources of information, known as cue integration through which the brain weights different depth cues based on how reliable or informative they are in a given viewing instance (Barry G Blundell, 2011; Cutting, 1995; R. Patterson, 2012; Watt & MacKenzie, 2013). Cutting and Vishton have presented relative strength of depth cues according to viewing distance, segmenting the space around an observer into three classes (Cutting, 1995): personal (<1.5m), action (1.5~30m) and vista (>30m) space. In personal space, binocular depth cues (only perceivable by both eyes including binocular disparity and convergence) are very strong and effective but the strength of these cues decreases with distance. In action space, occlusion is the strongest depth cues followed by relative height in the visual filed, relative size of the same object at different depth, motion parallax, binocular disparity, convergence and accommodative focus. In vista space, a handful of monocular depth cues (perceivable by one eye such as occlusion, relative size, relative height and atmospheric haze) are dominant. This suggests that within each space, some cues are stronger and more effective than others in human perception of depth.

Display Technologies and Affordable Depth Cues. Based on the knowledge about the human visual system, visual displays can be classified into four different families (Table 2.1), by their capability of presenting different depth cues (B G Blundell & Fihn, 2012; Reichelt, Häussler, Fütterer, & Leister, 2010). For the consistency of terminology, we will use monocular / binocular for depth cues and monoscopic / stereoscopic for types of displays.

Table 2.1 Families of visual display technologies and affordable depth cues
* indicates binocular depth cues

Depth Cues \ Display Family	F1. Monoscopic	F2. Stereoscopic	F3. Stereoscopic w/ multiple views	F4. Volumetric
Perspective cues	X	X	X	X
*Binocular disparity**		X	X	X
*Convergence**		X	X	X
Motion parallax			X	X
Accommodation				X

Monoscopic displays (family 1), confusingly and commonly known as 2D displays, can convey 3D depth information by perspective projection of 3D structures on to a single display surface. They are capable of providing a group of monocular depth cues, also known as *pictorial* or *perspective cues* such as occlusion, relative height, relative size, linear perspective, shading and texture gradient (Reichelt et al., 2010; Watt & MacKenzie, 2013).

Stereoscopic displays (family 2) can additionally provide binocular depth cues (i.e., binocular disparity and convergence) by delivering a pair of slightly different images to each eye taken from a single, fixed viewpoint (R. E. Patterson, 2015; Watt & MacKenzie, 2013). This family of displays presents images onto a fixed focal plane, and requires special glasses or headgear to convey separate views to each eye (e.g., 3D TVs).

Stereoscopic with multiple views displays (family 3) also present images on a single focal plane, but provide an additional depth cue afforded by head movements, motion parallax, by either presenting many views taken from multiple viewpoints or tracking an observer's head (Chen, Cranton, & Fihn, 2012; Reichelt et al., 2010). Typical examples of this family of displays include multi-view displays and VR head-mounted displays (e.g., Oculus). When viewing through these displays, moving one's head from side to side produces a different viewpoint of the same scene, leveraging motion parallax to provide more natural viewing experiences.

The last family of displays, *volumetric displays (family 4)* can naturally support for accommodative focus. They mainly differ from all other families of displays in the use of voxels, 3D equivalents of pixels in fixed-focal-plane displays (Barry G Blundell & Schwarz, 2000; Reichelt et al., 2010). These displays illuminate voxels to create virtual objects within a 3D volume, for example, by using either multiple static focal planes (spatial multiplexing or static volume technique) or a moving image plane (temporal multiplexing or swept volume technique) in a 3D space. Since voxels physically occupy a 3D space, many depth cues available in physical objects are also available in virtual objects are satisfied naturally. Binocular disparity and motion parallax exist naturally rather than simulated by displays, and accommodation and convergence are not in conflict as is typical in common VR and AR displays (Barry G Blundell, 2012; R. Patterson, 2012; Reichelt et al., 2010). However, this family of displays are usually expensive and require complex optical mechanisms, resulting in bulky hardware form factors with small field-of-views (Chen et al., 2012; Dunn et al., 2017; Reichelt et al., 2010).

Human Depth Perception in AR. Human observers see augmented environments through AR displays where both physical and virtual objects can affect perceived depth of each other. Empirical studies have shown that depths of physical objects are more accurately judged than those of virtual objects in both personal and action space (Jerome & Witmer, 2005; McCandless, Ellis, & Adelstein, 2000; J P Rolland, Gibson, & Ariely, 1995). In personal space, Ellis and Menges (2016) reported degraded depth judgement performance with a monoscopic display as compared to a stereoscopic one. Swan, Jones, Kolstad, Livingston, and Smallman (2007) compared egocentric depth judgement performance in action space with a stereoscopic optical see-through head-mounted display. They found that egocentric depth to virtual objects is underestimated in AR but even more underestimated in VR. Spatial relationships between virtual and physical objects can also affect perceived depth to virtual objects. Kirkley Jr (2003) found that placing virtual objects on the ground plane improved depth judgements. In a study on automotive AR, Tonnis and Klinker (2006) found that the direction of a virtual arrow is better perceived when it is attached to a car body using a virtual pole rather than hovering over the car. Virtual objects can also affect perceived depth to physical objects. Smith, Doutcheva, Gabbard, and Burnett (2015) reported that distance to a pedestrian was underestimated when augmented and viewed through a HUD that overlays a virtual box atop the pedestrian. However, aforementioned user studies have used fixed-focal-plane displays (especially in display family 1 and 2) which have inherent limitations in conveying depth cues, thereby providing limited understanding about human depth perception in AR.

Human Depth Perception via AR HUDs. For automotive application of AR, researchers have conducted empirical studies on depth perception of virtual objects in action space, using prototypes of optical see-through HUDs which encompass all four families of displays discussed earlier: monoscopic, stereoscopic, multi-view and volumetric display. Tasaki, Moriya, Hotta, Sasaki, and Okumura (2012) examined a registration problem caused by car vibrations using monoscopic AR HUDs on the road. They proposed a method that hides the AR graphics when large vibrations are detected, showing that drivers were able to interpolate the position and orientation of hidden AR graphics based on the flow of AR images rendered just before hidden. Hotta, Sasaki, and Okumura (2011) improved depth perception of monoscopic AR HUDs by using an animation effect of AR cues that move toward the real world target. Broy et al. (2014) examined design factors for stereoscopic AR HUDs suggesting that 5~8m of focus distance would be a good trade-off for fixed focal plane stereoscopic displays in consideration of both observers' depth judgement accuracy and visual comfort. However, they argued that with fixed focus distance displays, AR graphics in a depth layer can hide objects in other depth layers. Takaki, Urano, Kashiwada, Ando, and Nakamura (2011) prototyped an autostereoscopic, multi-view windshield display that supports not only accurate binocular disparity but also motion parallax. In their experiment using a perceptual matching task within a range of 50m, participants showed significant improvement in depth judgements with the multi-view display as compared to a stereoscopic display, suggesting that motion parallax is one of the most dominant and effective depth cues in action space. Finally, Bark, Tran, Fujimura, and Ng-Thow-Hing (2014) prototyped a 3D volumetric AR HUD and conducted a depth judgement study in an outdoor setting where observers were asked to make a forced-choice among physical targets which was perceived to be closest to virtual objects placed at 9~26m. Accuracy with the volumetric display was higher (97%) than that with a monoscopic display (32%). In sum, these studies suggest that the more depth cues are available, the better egocentric depth perception is expected. However, aforementioned studies quantified depth judgment capability of stationary observers, which might differ from that of fast moving observers such as vehicle drivers.

Human Performance in AR / VR. Despite known benefits of advanced display technologies in human depth perception, their effects on human performance in higher level spatial tasks are modulated by several factors. A recent comprehensive review (McIntire, Havig, & Geiselman, 2014) on stereoscopic displays and human performance in various spatial tasks reports that stereoscopic displays are beneficial to various tasks; out of 184 experiments, 60% reported benefits of stereoscopic displays over monoscopic displays, 15% reported marginal benefits only in some performance measures, and 25% reported no benefit. The review also shows differential benefits of stereoscopic displays depending upon the type of spatial tasks: distance judgement (57%), visual search (65%), spatial understanding (52%), object manipulation (67%) and navigation (42%). In addition to the task-type, in-depth analysis revealed other modulating factors such as (1) salience of monocular depth cues, (2) task difficulty, (3) viewing distance, (4) user expertise and (5) movement. The review suggests that stereoscopic displays are less beneficial when strong monocular depth cues are available for easy tasks requiring far-field interactions done by experienced moving operators. In spite of the authors' comprehensive efforts, most experiments reviewed (98%) were conducted in either VR or video see-through AR, where depth-cue-rich real-world views were replaced by either virtual worlds or video feeds which offer different depth cues and thus consequences on human performance, as compared to optical-see through AR (Jannick P Rolland & Fuchs, 2000).

2.2.3 Ecological Interface Design for Driver Interfaces

EID has been successfully applied to many domains such as telecommunication, aviation, nuclear power plant operation, manufacturing process control, healthcare and medicine (Burns & Hajdukiewicz, 2013). In the driving domain, Seppelt and Lee (2007) designed an in-vehicle display for adaptive cruise control that presents emergent shapes depending upon the relationship between the driver's car and the lead vehicle (time to collision and timed headway). A similar approach for lane change warning revealed that EID-based designs outperformed an existing design in driver judgement accuracy and confidence (Lee, Hoffman, Stoner, Seppelt, & Brown, 2006).

There is little research or practical efforts to incorporate EID into AR interface design, in spite of the documented and perceived benefits of AR. Kruit et al. adopted EID to design an AR HUD-based rally car driver support system that depicts an ideal, predicted path of the car and boundary curve to show the capability and limitation of the car. However, the effect of the new interface design on user performance was not reported (Kruit, Amelink, Mulder, & van Paassen, 2005).

We purport that EID is likely well-suited to AR interface design for vehicle drivers, since driving is a spatiotemporal task that demands drivers' appropriate information processing and responses to dynamic environmental changes. Furthermore, the EID leverages an established benefit of AR – namely, the ability to overlay information directly onto real-world objects, thereby affording direct perception of both virtual and real-world information.

3. Information Requirements

3.1 Objective

Requirement analysis aims to extract design implications for pedestrian collision warning by answering RQ1: What are the work demands of automobile driving - constraints that shape the driver's behavior? RQ2: What information should be available to the driver - content and structure of information?

3.2 Method

To derive information requirements for interface design, we first examined environmental and cognitive constraints that shape the driver's behavior. Work domain analysis (WDA) captured environmental constraints imposed on the driver's behavior for safe transportation. Control task analysis (CTA) further revealed cognitive constraints (required cognitive activities) for the driver to avoid collision with pedestrians. From the results of WDA and CTA, we consolidated information requirements and design implications for pedestrian collision warning. To be more specific, information requirements include information content (work domain variables) and structure (relationships among variables) for pedestrian collision warning.

3.2.1 Work Domain Analysis

We started our analysis by examining environmental constraints that affect the driver's behavior in any situation, because any intention of the driver cannot be realized against environmental constraints (e.g., physical law of motion). We first defined the system boundary as the near traffic of the driver's own car, then decomposed the system into components along two dimensions; functional and physical. In the functional dimension, we decomposed the system from abstract purposes into concreate functions by asking why-how (or ends-means relationship) questions. The higher level purposes (ends) could be achieved by lower level components (means). In the physical dimension, the system was decomposed into physical components with part-whole relationship. As a tool for WDA, we used a two dimensional *abstraction-decomposition space* (Vicente, 1999, p. 157) where abstraction hierarchy (AH) reveals the means-ends relationship while decomposition hierarch (DH) captures the part-whole relationship. In sum, WDA provided a functional and physical model of automobile driving. The analysis initially conducted was based on literature review and iteratively revised by discussion with a group of human factors researchers who are also experienced drivers.

3.2.2 Control Task Analysis

We further analyzed cognitive constraints that affect the driver's behavior to avoid collision in a cross traffic situation. We selected this goal and situation intentionally, to derive specific information requirements for pedestrian collision warning. First, a *normative model* of the driver's cognitive process was built by identifying inputs (required information about system states), outputs (required action on the work domain), and activities (data processing activities that transform inputs to outputs) for the driver to avoid collision. We then developed a *formative model* of the driver's cognitive process by identifying possible opportunistic shortcuts in the process that represents expert's capability of bypassing certain steps in human information processing. It is notable that CTA describes what needs to be done in a particular situation, independent of by whom (i.e., the operator can be a human driver or a self-driving car). However, we assumed a human driver since we aim to design AR interfaces for the human. The product of CTA was represented by a *decision ladder* (DL, Vicente, 1999, p. 187) to capture not only the processes but also the possible shortcuts.

3.3 Result

3.3.1 Environmental Constraints and Information Requirements

Gibson and Crooks (1938) conducted an insightful and comprehensive theoretical analysis on automobile driving. They defined driving as a matter of moving toward the destination while keeping the car running within the *field of safe travel* (FoST). It is a kind of invisible tongue protruding forward along the road within which certain behavior is possible without collision (Figure 3.1). The overall direction of the FoST (heading) is guided by the destination. At every moment, the driver's FoST can be bounded and shaped by external

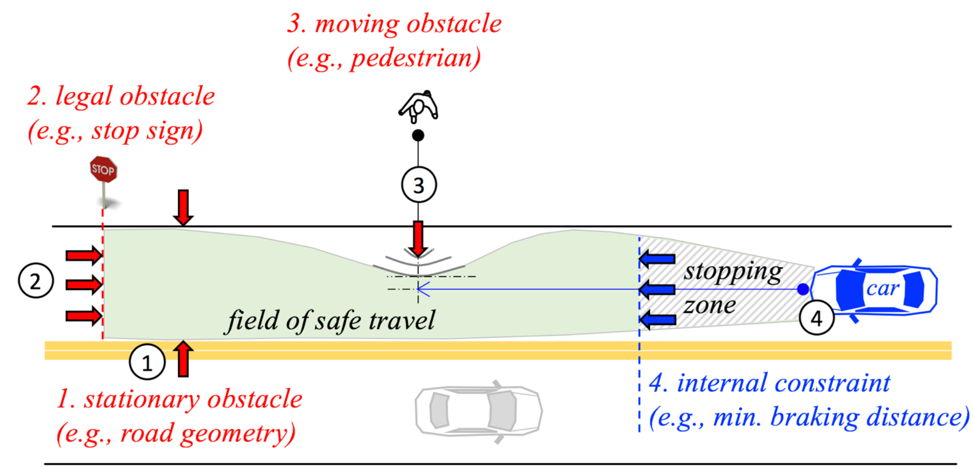

Figure 3.1 Environmental constraints that shape the driver's behavior.
Driver's field of safe travel can be shaped by external (red) and internal (blue) constraints. The field of safe travel and stopping zone are adapted from Gibson and Crooks (1938).

or internal constraints. External constraints include stationary obstacles (e.g., road geometry), moving obstacles (e.g., other vehicles, pedestrians and animals), and legal obstacles (e.g., traffic signals, road sings and markings). The internal constraints, limitations of the car's moving capability (e.g., minimum braking distance and inflexibility in sharp turns at high speed), can contract or shear off the driver's FoST as well. It is notable that the FoST exists objectively as an actual field regardless of whether the driver perceive it correctly or not (Gibson & Crooks, 1938, p. 455). The effect of a moving obstacle on the driver's FoST can be estimated by not only a projection of a moving obstacle but also the projection of the driver's own car to the point of intersection of the two paths (Figure 3.1 and Gibson & Crooks, 1938, p. 464).

Motivated by Gibson & Crooks's work, we analyzed the work domain of driving and represented it into a two-dimensional space that consists of an abstraction hierarchy (AH) and decomposition hierarchy (DH) as shown in Figure 3.2. In the functional dimension, 'safe transportation' was selected as the reason for the system's existence (*functional purpose*). Safe transportation means maintaining enough separation among road actors in the system level and maintaining the driver's FoST large enough in the component level. For safe transportation, the driver should comply with the social law of traffic rules and

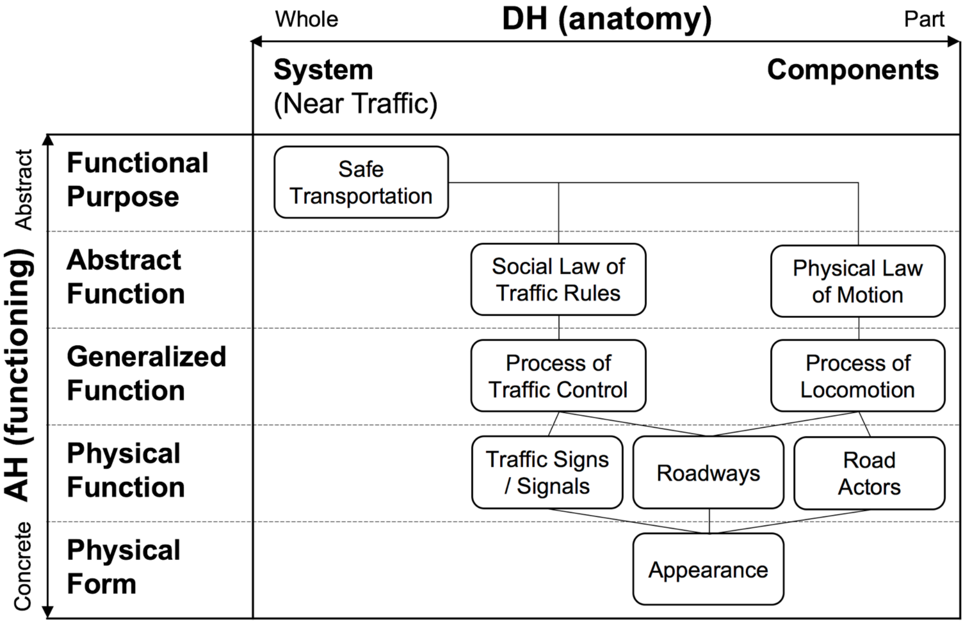

Figure 3.2 The work ecology of automobile driving for safe transportation.
The result of work domain analysis (physical and functional mechanism) represented in abstraction-decomposition space. Reprinted with permission from Kim et al. (2016).

physical law of motion (*abstract function*). Governed by these laws, safe transportation can be achieved by actual process of traffic control and road actors' locomotion (*generalized function*). These processes are realized by system components (*physical function*) such as the driver's own car, roadways, other road actors, traffic signal and signs that function as a locomotion vehicle, paths, and / or obstacles. Finally, the function of each component can be embodied into different forms of equipment with different perceptual appearance (*physical form*). In the physical dimension, the system boundary was defined as the near traffic of the car and decomposed into lower level components such as road signs, traffic signals, roadways and road actors including the driver's own car.

WDA resulted in information requirements for safe transportation which are valid in any situation to any driver. However, we focused on those relevant to collision avoidance for our driver interface design. To make sure the entire system is working properly (safe transportation), we need to know the system states with measurable variables. Table 3.1 summarizes information requirements: contents (which variables should be measured) and

Table 3.1 Information requirements identified by WDA for safe transportation
Information contents (work domain variables) and structure (relations/constraints among variables). Reprinted with permission from Kim et al. (2016).

Level	Variables		Constraints	
			Single Variable	Among Variables
Functional Purpose	System state variables	*relative position to obstacles; hw, g* *relative position to the destination*	$hw > HW^*$ *(threshold)*	$hw = \lvert g_m - g_c(v_m / v_c)\rvert$ $g = f(s, p, v)$
Abstract Function	Process governing laws			$a = F/m$ $a = dv / dt = d^2p / dt^2$
Generalized Function	Process variables (components' current states)	*road actors' positions; p(t)* *road actors' velocities; v(t)* *road actors' accelerations; a(t)* *state of traffic signals* *relevant road signs* *roadway condition*	$v < v_{max}$ $a_{min} < a < a_{max}$	
Physical Function	Components' functional capabilities	*moving capabilities;* a_{min}, a_{max} *# of signal states* *topography (road network)*		
Physical Form	Components' appearances	*size of obstacles; s* *road geometry; w (lane width)* *destination*	$s < s_{max}$ $w < w_{lane}$	

structure (what relationships should be maintained for safe driving). The variables were identified by asking "How could we measure each level in AH?". At the highest level, safe transportation can be measured by enough separation or gaps among road actors. For example, the relative position to an obstacle can be represented by a variable, headway *hw(t)*, which is changing over time as a function of both a moving obstacle's and the driver's own car's velocity (v_m and v_c) and gaps (g_m and g_c) from the intersection of the two paths. Road actors' movement and gaps can be measured and predicted from variables such as position (p), velocity (v), and acceleration (a). Each road actor can be characterized by moving capability such as maximum speed (v_{max}), minimum braking distance, or maximum acceleration / deceleration (a_{max}). Finally, perceptual appearance of each component is quantified by its shape and size (e.g., s_{max}). Most importantly, all the defined variables cannot be out of each component's capability (single variable constraints, e.g., $v < v_{max}$) and are related to each other (multivariate constraints, e.g., $hw = |g_m - g_c(v_m / v_c)| > HW^*$) to avoid collisions governed by physical law of motion.

3.3.2 Cognitive Constraints and Information Requirements

To avoid collision in cross traffic situation, the driver needs to conduct a series of cognitive activities (cognitive constraints) that will define his/her behavior. CTA captured this type of constraints. We first developed a normative model (what should be done) of the driver's cognitive process and further developed a formative model (what could be done) assuming the driver has a pedestrian collision warning.

A normative model of the driver's cognitive process. Figure 3.3 illustrates the driver's data processing activities that need to be performed and state of knowledge resulting from data processing. The driver needs to keep monitoring near traffic to (1) detect any obstacle on the own car's path. Once an obstacle is detected, it needs to be (2) localized for further observation (p_m). Based on observed shape and size (s_m), the driver (3) identifies type of

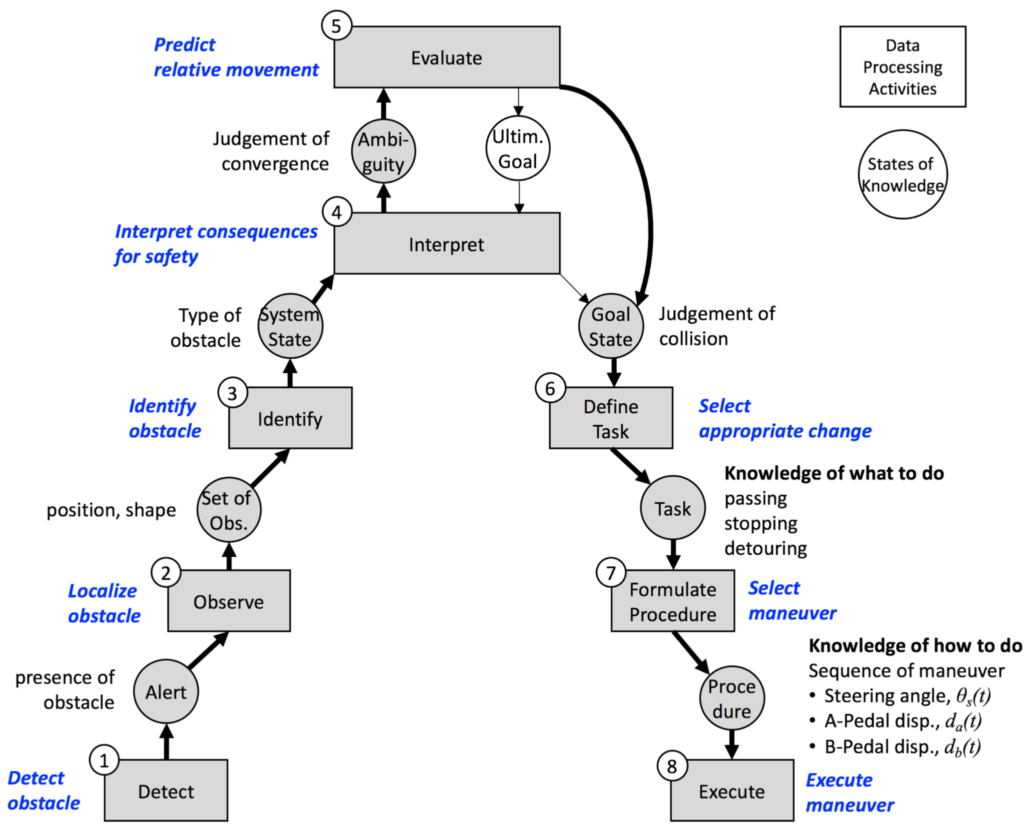

Figure 3.3 A normative model (what should be done) of the driver's cognitive process to avoid collision in cross traffic situation.

Table 3.2 Information requirements identified by CTA for collision avoidance in cross traffic situation

Inputs (required information about system states for each activities), outputs (required action on the work domain) and constraints among variables

Step #	Input	Activity	Output	Constraints
1	• Own car's path	*Detect* presence of obstacles around the own car's path	• Obstacles' presence	
2	• Obstacles' presence	*Localize* obstacles	• Obstacles' position, $\boldsymbol{p_m}$	
3	• Obstacles' position, $\boldsymbol{p_m}$ • Shape, size, $\boldsymbol{s_m}$	*Identify* obstacles	• Type of obstacle	• Past experience or rule for classifying objects (e.g., by shape and size, $s < s_{max}$)
4	• Obstacles' heading, $\boldsymbol{v_m}$ • Own car' heading, $\boldsymbol{v_c}$	*Interpret* consequences for safety	• Judgement of convergence, ***CON***	• CON = {0,1} • If ($\boldsymbol{v_m}$ X $\boldsymbol{v_c} \neq 0$) {CON = 1; go to the next step;} else {CON = 0; keep driving;}
5	• Obstacles' position, $\boldsymbol{p_m}$ • Obstacles' velocity, $\boldsymbol{v_m}$ • Own car's position, $\boldsymbol{p_c}$ • Own car's velocity, $\boldsymbol{v_c}$	*Predict* obstacles' relative movement	• Judgement of collision, ***COL*** • $\boldsymbol{g_m}$, $\boldsymbol{g_c}$, ***hw***	• COL = {0,1} • Headway threshold (e.g. HW* = $\boldsymbol{s_c}$) • $hw = \lvert g_m - g_c (v_m / v_c) \rvert$, $g = f(s, p, v)$ • If ($hw<HW*$) {COL=1; go to the next step;} else {COL=0; keep driving;}
6	• Judgement of collision, ***COL***	Select appropriate change	• Task, ***TASK***	• TASK = {passing, stopping, detouring} • Availability of adjacent lanes • Moving capabilities of the car
7	• Task, ***TASK***	*Select* maneuver	Sequence of maneuver • Steering angle, $\boldsymbol{\theta_s(t)}$ • A-Pedal disp., $\boldsymbol{d_a(t)}$ • B-Pedal disp., $\boldsymbol{d_b(t)}$	• Possible Range of controls $\theta_s < \theta_{s,max}$, $d_a < d_{a,max}$, $d_b < d_{b,max}$ • Own car's moving capabilities $a_{c,min} < a_c < a_{max}$
8	• Sequence of maneuver	*Execute* maneuver	Action on work domain	

the obstacle (e.g., car, pedestrian, or animal) and (4) interprets the consequence of the detected obstacle; whether its path is converging to the car's path or not. If not (CON=0), the driver keeps driving. If the obstacle is approaching to the own car's path, the driver needs to (5) evaluate whether it will collide with the own car or not by predicting relative movement of the obstacle. This estimation requires work domain variables including both moving objects' (i.e., own car and obstacle) position and speed (p_m, p_c, v_m *and* v_c). If collision is expected (COL=1), the driver needs to (6) decide appropriate changes in his/her operation (e.g., accelerating to pass, braking to stop, or changing the lane to detour) to avoid collision. The selected task needs to be done by (7) a series of appropriate maneuvers that can be described by specific values of control parameters over time, such as steering angle (θ_s) and pedal displacements (d_a, d_b). Finally, the driver should (8) execute the maneuvers as intended.

As a result of CTA, we were further able to determine which work domain variables and constraints are relevant to a specific goal (collision avoidance) in a particular situation (cross traffic). Table 3.2 summarizes detailed description of information requirements for each data processing activities. Some variables and constraints were uniquely identified in CTA such as steering angle, pedal displacements and possible ranges of those controls (e.g., $\theta_{s,max},\ d_{a,max}\ \ d_{b,max}$).

A formative model of the driver's cognitive process with warning. Since this work aim to design pedestrian collision warning, we further developed a formative model by identifying possible shortcuts that can be facilitated by pedestrian collision warning. For example, if an AR warning interface highlights a pedestrian, it might activate a shortcut ("A" in Figure 3.4) so that the driver will be aware of the presence, position and type of an obstacle in his/her path at the same time by only seeing the warning. Although we cannot predict which shortcut might be activated or not, even whether shortcuts have positive or negative effect

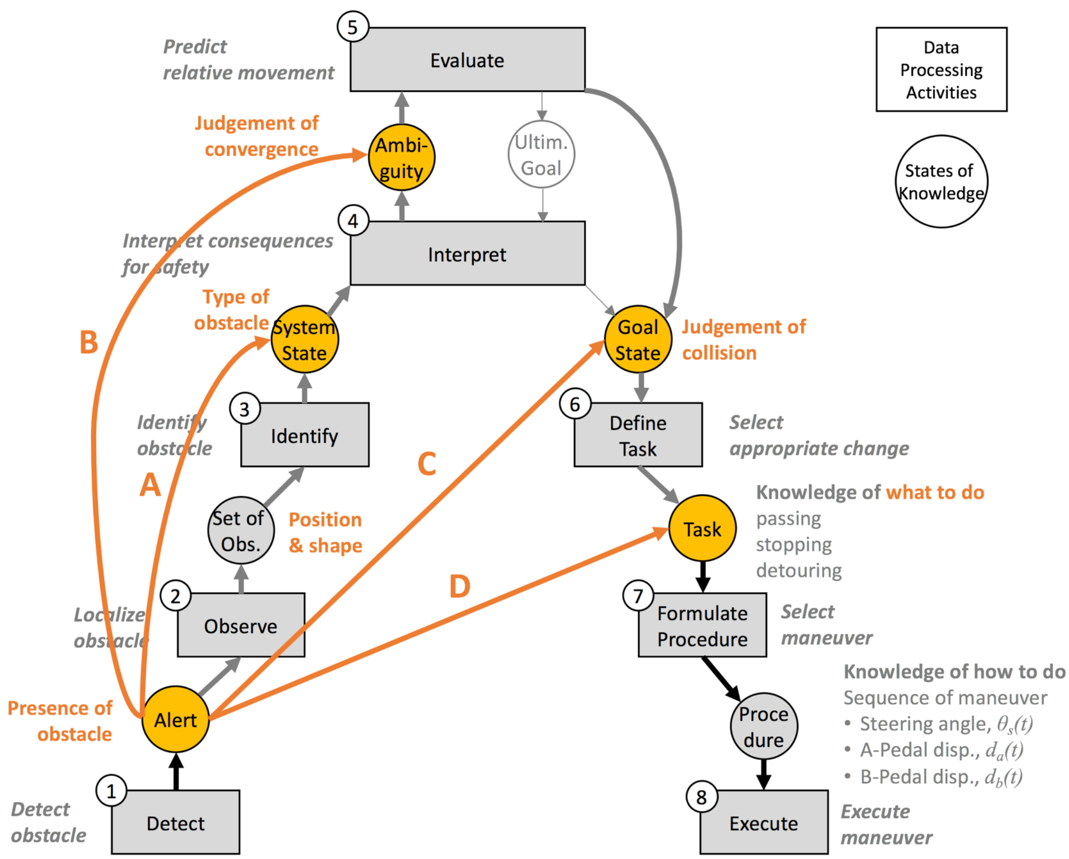

Figure 3.4 A formative model (what could be done) of the driver's cognitive process with pedestrian collision warning.
The decision ladder represents possible shortcuts that might be activated by warning.

on the driver experience, the DL captured possible alternative paths through the information processing system that might be caused by pedestrian collision warning. In this way, the DL modeled an active, constructive nature of the driver information processing.

3.4 Discussion and Design Implications

This phase of research efforts identified (1) *constraints* that affect the driver's behavior and (2) information *requirements* for pedestrian collision warning. The driver's behavior can be shaped by the destination but also bounded by environmental constraints such as stationary, moving and legal obstacles (Figure 3.1). To avoid collision, the driver needs to detect, localize, identify moving obstacles and evaluate the possibility of collision (cognitive constraints). More importantly, pedestrian warnings might let the driver bypass some steps in the cognitive process through opportunistic shortcuts (Figure 3.4).

In sum, WDA & CTA revealed required content (what information should be measured and derived) and structure of information (how should information be related and organized). Figure 3.5 summarizes information requirements for pedestrian collision warning. To support the driver's cognitive process, pedestrian's *relative* position, velocity (heading) and ultimately the predicted minimum spatial gap (headway) should be available.

Implications for interface design

- Sensors; Although some variables (e.g., headway or gap) can be derived from others, primitive variables (moving objects' position, velocity and acceleration) should be directly measured by sensors or available via V2X communication (e.g., vehcile to pedestrian communication, Honda, 2015).
- Models; Based on physical law of motion and given road geometry, pedestrians' movement should be predicted relative to the driver's own car.
- Context-sensitive interface; When collision is predicted, the dynamics of spatial gaps between the driver's own car and pedestrians should be available to the driver. This is the ultimate information the driver needs to make sure everything is going well

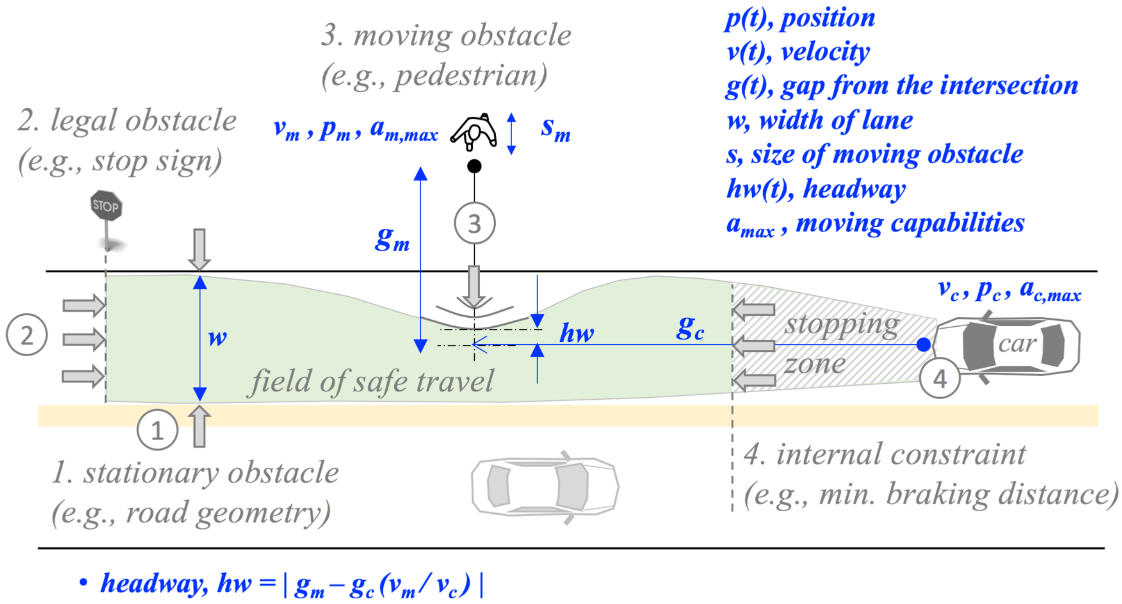

Figure 3.5 Identified information content (work domain variables to be available) and structure (relationships among variables, represented by an equation) for pedestrian collision warning.

(functional purpose in AH, see Table1) and to select appropriate reaction (one the cognitive activities in DL, see STEP6 in Table 3.2).

- The interface should provide all the required information in an organized manner such that the driver is able to know not only whether collision would happen (high level overview), but also where pedestrians are approaching (low level details) for skilled performance.
- Finally, the display could leverage the power of shortcuts (bypassing demanding interpretation or evaluation steps, see Figure 3.4) in the driver's cognitive process.

Implications for usability evaluation

- From WDA; Our design intention is limited to pedestrian collision warning. However, the driver needs more information for safe transportation (e.g., current state of traffic signals, relevant road signs and road network to get to the destination, as identified in Table 3.1). Therefore, usability evaluation of pedestrian collision warning could consider the effect of warnings not only on the pedestrian collision avoidance but also on other task performance such as navigation.

- From CTA; Since pedestrian collision warning might facilitate shortcuts in the driver's information processing, usability evaluation could include process measures to evaluate the driver's state of knowledge at each stage to reveal which shortcut is activated.

4. Driver Interface Design

4.1 Objective

This phase aims to design an AR driver interface for pedestrian collision warning by answering RQ3: How should critical information regarding pedestrian collision avoidance be presented to the driver (perceptual forms of interface elements)?

4.2 Method

To design a driver interface that meet information requirements identified in the previous phase, we first considered unique design factors for AR graphical representations. Inspired by design principles of ecological interface design (Vicente, 1999, p. 295), we designed specific forms of interface elements and organized them to make the invisible dynamics of cross traffic salient. Analogical representations were used to map work domain variables onto abstract geometric shapes. A design metaphor was developed to organize the interface elements such that the emergent feature looks similar to a familiar object in people's everyday life.

Task demands of driving impose unique constraints on drivers' cognitive process; they cannot allocate all attention resources to interactions with interfaces. Therefore, we should carefully display correct information with the most appropriate ways, timing, and placement. Furthermore, outdoor use of optical see-through AR HUDs made us consider additional design factors for our interface design. All design factors were embodied in our design metaphor as a whole.

- *Frame of reference* is one of the most important factors in AR graphics design. Graphics can be shown in exocentric (e.g., top down view) or egocentric (the driver's perspective) manner;
- *Registration* (or location) of graphics are another critical factor. Graphics can be directly attached to real world target objects (world-fixed or conformal), fixed to certain locations on the display regardless of the target (screen-fixed) or associated with, but

not directly attached to, real-world targets (world-associated, Gabbard, Fitch, & Kim, 2014);

- *Information density* is amount of graphics to be shown at a given time and space;
- *Shape* of graphics should embody design metaphors for ease to understand;
- *Size* of the graphics is important for cue visibility and occlusion of drivers' field of view;
- *Color and brightness* can contribute to visibility and perceived meaning;
- *Intensity* (or transparency) of the graphics is critical especially in optical see-thru AR displays not only for their visibility but also visibility of the target objects behind the graphics; and;
- *Timing* of AR interface cues is a key design factor for appropriate attention guidance and decision support.

Ecological interface design framework provides the SRK (Skills, Rules, Knowledge) taxonomy of human cognitive control to help designers determine how information should be displayed to be compatible with the various mechanisms that people have for processing information (Vicente, 1999). A skill-based behavior (SBB) is a sensorimotor behavior based on real time processing of environmental changes with little or no conscious attention. SBB can be supported by direct perception and interaction via time-space signals. A rule-based behavior (RBB) is an appropriate reaction to a familiar cue in the environment based on the stored rules. RBB can be supported by one-to-one mapping between work domain constraints to signs in the interface. A knowledge-based behavior (KBB) requires analytic reasoning based on a mental model typically in unfamiliar situations. KBB can be supported by externalized work domain models (i.e., visualization of goal-relevant constraints) in the form of structured symbols.

Interface design is realized by a set of graphical representations. Graphical user interfaces typically use a combination of three different types of representational formats: *propositional*, *metaphorical* and *analogical* (Bennett & Flach, 2011, pp. 119-122). Propositional format uses alpha-numeric labels to represent abstract concepts or exact values. Metaphors leverage people's experience in familiar domains by using graphical representations that resemble familiar objects. Since they only employ structural similarity of other things, users need to learn functional differences via interaction. Analogies, on the

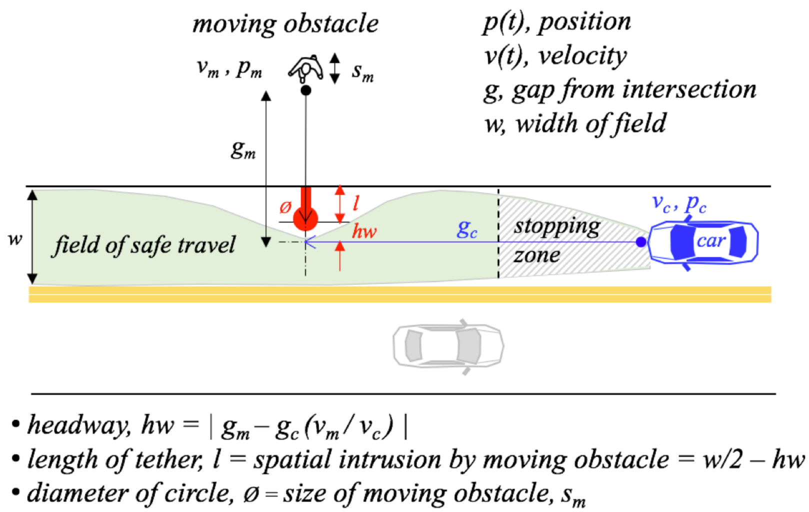

Figure 4.1 Virtual shadow design metaphor
Mapping between physical forms of interface elements and work domain variables & constraints. Reprinted with permission from Kim, Isleib, and Gabbard (2016).

other hand, utilize both structural and functional (or behavioral) similarities of referents with abstract geometric shapes.

This work leveraged the benefits of both analogies and metaphors. We first designed abstract geometric shapes by mapping work domain variables onto perceptual forms of interface elements (e.g., shape, size or location). Then, interface elements were integrated based on constraints among work domain variables. We intended to configure an emergent feature that represents the dynamics of cross traffic. Since configural displays sometime look strange to new users and require time to practice (Bennett & Flach, 2011, p. 104), we went further to leverage the benefit of metaphors by making the emergent feature looks similar to a familiar object in drivers' everyday life.

4.3 Result: The Virtual Shadow

We propose a novel driver interface for pedestrian collision warning that casts ***virtual shadows*** of approaching obstacles that are immersed in the real world, taking advantage of AR HUDs. To support SBB, we present the shadow in egocentric frame of reference for direct perception from the driver's perspective. For the registration of AR cues, we present the shadow in a world-fixed manner such that it moves along with the target obstacle and appears larger as the driver approaches. RBB can be supported by a clear sign of collision. This is realized by associating work domain variables and constraints (identified in Figure 3.5) with perceptual forms of interface elements (Figure 4.1). The location of the circle shows the predicted location of collision. The shape and size of a virtual shadow reflects the type and size of an approaching obstacle. The direction of the tether depicts the direction from which the obstacle is approaching. The length of the tether indicates expected spatial intrusion by a detected obstacle when the car would arrive at the intersection of the obstacle's path. The red color of the shadow warns the driver of an urgent situation that requires an immediate response. Finally, KBB can be supported by the emergent feature that visualizes the dynamics of the spatial gap between the driver's car and moving obstacles over time (as the car moves). We propose that repeated use of this AR interface would help drivers develop an accurate mental model of the dynamic environment, especially with respect to drivers' time-distance judgments between own-car and moving obstacles.

4.4 Discussion

The resulting AR driver interface design, the virtual shadow, was based on some assumptions. We assumed capabilities of sensor or communication technology. The accuracy of pedestrian detection technology was assumed to be perfect which is not true at this moment of time (Benenson et al., 2014), although it has been improving by advances in computer vision and multi-sensor fusion technology (Benenson et al., 2014; Gepperth, Sattarov, Heisele, & Flores, 2014; Jung, Lee, Yoon, Hwang, & Kim, 2006; Musleh, García, Otamendi, Armingol, & De la Escalera, 2010). All primitive variables (e.g., own car and pedestrians' position, velocity and acceleration) are assumed to be available from sensors or Vehicle to Pedestrian (V2P) communication (Honda, 2014; Hussein, García, Armingol, & Olaverri-Monreal, 2016; Olaverri-Monreal & Jizba, 2016). We also assumed perfect prediction of pedestrians' future movement by technology (e.g., activity forecasting, Kitani, Ziebart, Bagnell, & Hebert, 2012).

4.4.1 Possibilities: Facilitating Skilled Performance

The virtual shadow has potential to facilitate skilled performance via shortcuts in the driver cognitive process (e.g., shortcut "C" in Figure 3.4) since it provides all the required information (i.e., presence, location, heading of approaching pedestrians and predicted spatial gap) that the driver needs for appropriate decision in cross traffic situation. Furthermore, this shortcut might allow the drive to skip demanding steps so as to reserve their attentional resource to monitor other environmental changes. The virtual shadow can be interpreted as a signal, sign and symbol depending upon circumstances, since we designed it to support skill-based (by direct perception via time-space conformal graphics), rule-based (by one-to-one mapping between work domain variables and perceptual forms), and knowledge-based (by visualization of invisible functional mechanism of cross traffic) behavior. Finally, it can be extended to any cross traffic alert (other than just pedestrian collision warning) such as alerts to avoid collision with vehicles backing up in parking lots.

4.4.2 Limitations: Supporting Parts of Work Demands

One of the most notable limitations of the design is that the virtual shadow does not represent the entire work ecology. It does not represent all constraints that affect driver behavior (see Figure 3.1) that are essential for safe transportation. The driver needs more information such as possible paths to the destination, currently valid traffic signals and so forth which are not supported by the virtual shadow. Another limitation lies on the missing details in the shadow metaphor. The shadow does not represent the moving capabilities of obstacles which might be critical for the driver to predict possible boundary of obstacle's future position. In fact, road actors' moving capabilities are identified requirements in the abstraction hierarchy (see Table 3.1) but missing in the design. All these drawbacks can limit the benefits of ecological interface design; supporting users to cope with unanticipated events via knowledge based reasoning.

5. Analytic Usability Evaluation

5.1 Objective

The analytic usability evaluation aims to validate the new design concept with rapid prototypes before empirical evaluations with a high fidelity prototype, by answering RQ4: Do AR pedestrian collision warnings have the potential to improve the quality of driver information processing?

5.2 Method

We prototyped the virtual shadow design metaphor using augmented video (Soro et al., 2014) technique by overlaying AR graphics atop driving video footage. For the usability evaluation, we conducted a heuristic walkthrough (Sears, 1997) in a driving simulator where expert evaluators mimicked driving while watching the augmented video, and predicted quality of the driver information processing as well as usability problems. A set of heuristics was developed and given to the evaluators.

5.2.1 Participants

We invited four experts (working professionals and graduate students) who met requirements for Virginia Tech's graduate certificate in Human-Computer Interaction and had experience in AR research.

5.2.2 Apparatus

Before implementing the design idea, we considered requirements for the fidelity of our early prototypes and evaluation settings; The interface should interact with environmental changes while driving; The driving scenario should be representative and realistic; Users should be able to interact with the prototype in a safe driving environment; And finally, the prototype should be easy to change for design iterations.

Augmented video. Keeping aforementioned requirements in mind, we implemented the design idea with a rapid prototyping technique that uses augmented videos. For ecological validity of the study, we used a naturalistic driving scenario. A camera (GoPro 3+) attached to a car captured driving footage with about 130° field of view while we drove along a pre-determined route near Virginia Tech campus in Blacksburg, VA. Computer generated graphics were overlaid atop the driving video footage using a video editing tool (Apple's Motion 5.3) afterward. To explore the potential opportunity of EID-informed designs as compared to currently available driver interfaces, we first prototyped an extant bounding box metaphor that highlights any detected pedestrians present within the pedestrian detection system's field of view (Benenson et al., 2014). Then the virtual shadow design metaphor was prototyped with the same driving scenario (Figure 5.1).

As described earlier, the spatial gap between the driver's own car and a moving obstacle is continuously changing as a function of the both moving objects' position and speed. The virtual shadow visualizes this gap by showing spatial intrusion by the obstacle (see equation in the Figure 4.1). Figure 5.2 compares two typical examples of virtual shadow dynamics. If the driver decelerates to avoid collision, the shadow of the approaching pedestrian will go further and disappear when the shadow leaves the vehicle's path (Figure

Figure 5.1 Visual warnings prototyped for the heuristic walkthrough
Bounding boxes (top) highlight detected pedestrians and the virtual shadow (bottom) visualizes dynamics of spatial intrusion by the approaching pedestrian. Reprinted with permission from Kim et al. (2016).

5.2.a). On the other hand, in some cases drivers may avoid collision by accelerating the car. Then the shadow of the pedestrian shrinks back (Figure 5.2.b) since the pedestrian will not get to the vehicle's path when the driver would pass the intersection of the two paths (pedestrian and own-car paths).

Driving simulator. For immersive driving experience, we used a driving simulator combined with augmented videos (Figure 5.3). Cognitive and manual demands of driving were substituted as approximates. We presented a small crosshair on the driving scene that

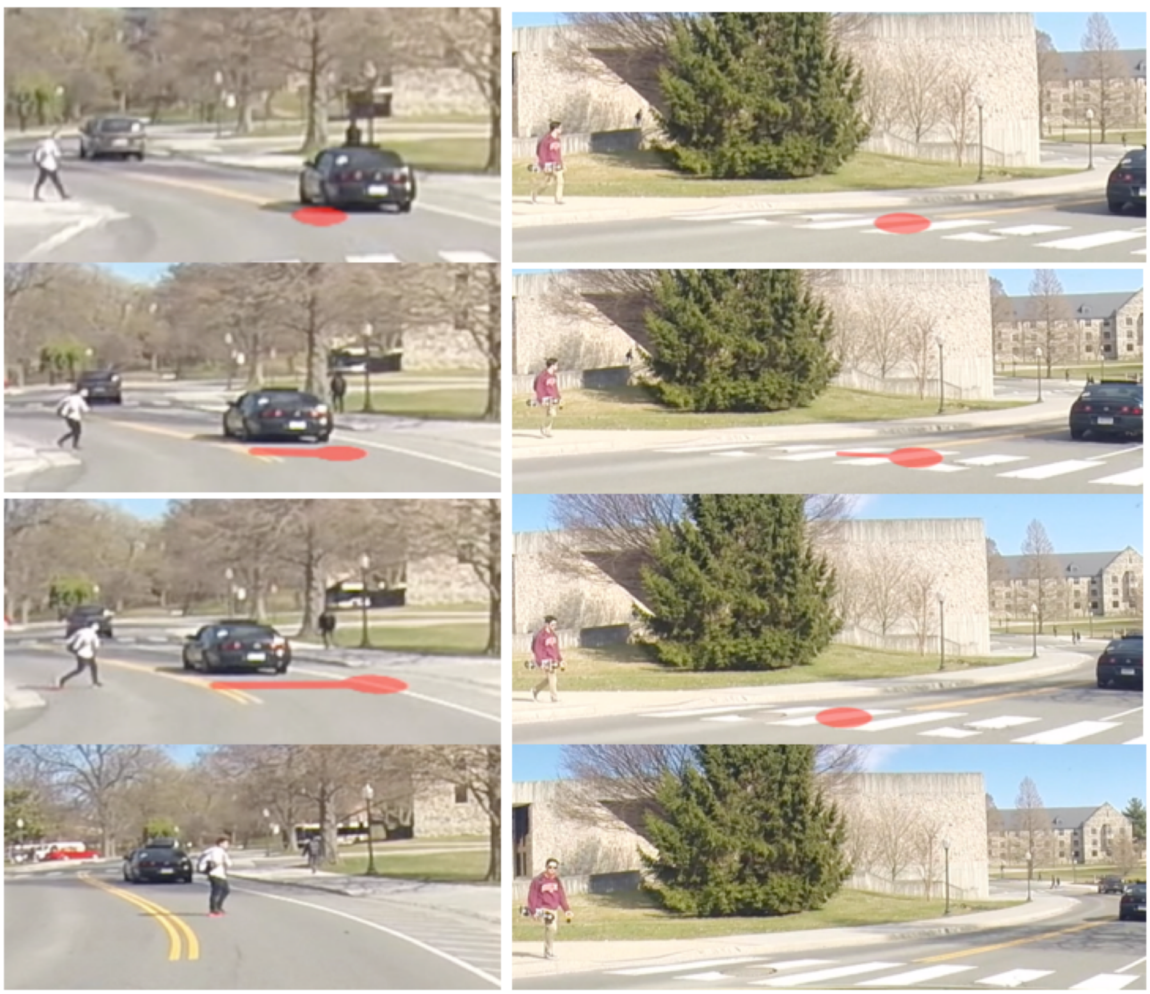

Figure 5.2 The virtual shadow in action
Two examples show how the driver's reaction affect interface dynamics (from the top to the bottom $t_0 \rightarrow t_1 \rightarrow t_2 \rightarrow t_3$). (a) the shadow starts stretching when the driver decelerates and disappears when the project of the pedestrian is beyond the vehicle's path; (b) the shadow starts shrinking back to the pedestrian and disappears when the driver accelerates so that the project of the car is beyond the pedestrian's path. Reprinted with permission from Kim et al. (2016).

was controlled by the steering wheel. During the driving session, we asked evaluators to match the crosshair to the center of their driving lane. Evaluators were also asked to follow driving direction provided by voice instructions that mimic GPS navigation aids. Furthermore, we asked evaluators to manipulate any required controls (e.g., pedals and turn signals) as they usually drive and as prescribed by the video (e.g., when the video shows car turning, evaluators were expected to use the turn signals and steering wheel).

5.2.3 Procedure

The heuristic evaluation consisted of four sessions. In the practice session, we briefly explained the procedure, interface design concepts and had experts get familiar with the driving simulator. In the walkthrough session, experts were asked to drive the car while using different interface designs (bounding box and virtual shadow). In the evaluation session, experts evaluated interfaces by predicting driver performance and identifying usability issues based on heuristics and their own expertise. Finally, in the retrospective

Figure 5.3 Driving simulator
A medium fidelity driving simulator combined with synthesized driving video footage provide immersive driving experience and served as an appropriate tool for usability evaluation. Reprinted with permission from Kim et al. (2016).

think aloud session, we replayed driving scenarios for each interface design and let experts reflect and think more deeply about interface designs. Experts gave comments on any usability concerns, and design improvement ideas. At the end of each session, we let experts explain the rationale behind their scores by asking "which design factors (see previous chapter) positively and negatively affected your ratings?"

5.2.4 Measures: Proposed Heuristics

A set of heuristics was developed aimed to predict driver workload and performance at each stage of human information processing (C. Wickens & Hollands, 2000). Thus, experts' predictions were focused on cognitive processes such as:

- *Attention-selective*; the information would catch the user's attention quickly
- *Attention-divided*; the information would not narrow the user's attention
- *Sensation*; the information would be salient enough to be sensed against the background
- *Situation awareness-perception*; the information would guide the user's attention to the relevant elements in a given context (the visuals would help the driver detect pedestrians)
- *Situation awareness-comprehension*; the information would help the user understand the consequence of the perceived elements (the visuals would help the driver identify dangerous pedestrians)
- *Situation awareness-projection*; the information would help the user project relevant environmental elements' status into the future (the visuals would help the driver predict the dangerous pedestrians' movement)
- *Decision*; the information would help the user recognize possible reactions and the urgency of reactions
- *Workload*; the information would likely help reduce task demands and the user's effort to complete the task

For each of the above categories, experts were asked to give scores by predicting driver performance compared to the control condition (not having any warnings): -3 strongly worse, 0 the same, and 3 strongly better than the control condition.

5.3 Results

The usability evaluation revealed that the virtual shadow is expected to improve driver performance at each stage of cognitive processing. Retrospective think aloud provided more detailed information about interface design factors that could be improved further to ensure better driver performance.

5.3.1. Quality of Driver Information Processing

The mean value of four experts' ratings on each category was calculated and plotted in a radar chart for comparison among conditions (Figure 5.4). Evaluation findings suggest the virtual shadow should outperform the control condition in all aspects addressed by heuristics including the driver's sensation, attention management, situation awareness, decision making and workload. On the other hand, the bounding box is expected to distract drivers from critical real world events, and not to help the driver identify and predict dangerous pedestrian's movement. It is also expected not to afford reduced workload in monitoring hazardous pedestrians.

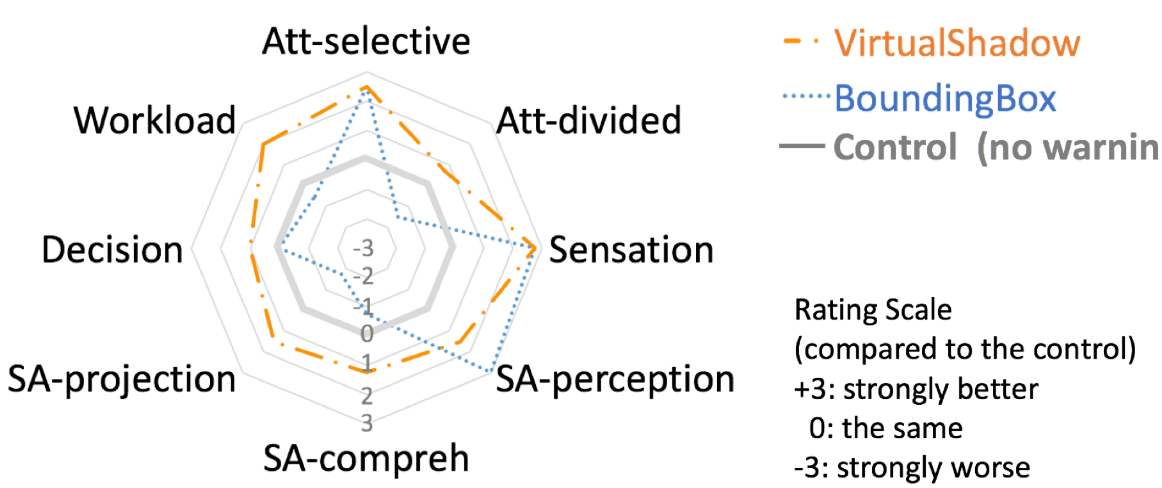

Figure 5.4 Results of the heuristic evaluation
Predicted user performance and workload by usability experts as compared to the control condition (no visual warning). Reprinted with permission from Kim et al. (2016).

Table 5.1 Relationship between predicted user performance and contributing design factors of the virtual shadow
Mapping between predicted user performance and contributing design factors of the virtual shadow. Reprinted with permission from Kim et al. (2016)

User Perf.	**Design Factors**							
Process	Density	Shape	Size	Loc.	Bright	Color	Intensity	Timing
Sensation		+		+		⊕	+	+
Attention	-		⊙	⊕			+	+
Perception	+			+	+	+	+	+
Compreh.	+	⊙		⊙		-		⊕
Projection	+	-		+				+
Decision	+	-	+	+		⊙	+	+
Workload	⊕	-		+		+	-	⊕

Relationship: ⊕ Strongly positive ,+ Positive, ⊙ Neutral, — Negative, ⊖ Strongly Negative

5.3.2. Relationship Between Interface Design Factors and Driver Performance

Experts' comments during the retrospective think aloud were captured into a matrix to visualize relationships between user performance and interface design factors. We calculated the mean values of four experts' ratings (with a 5 levels Likert scale) on relationships among user performance and contributing design factors. The round-off value of the means are interpreted back to the meaning and presented in a table for better visibility (Table 5.1). A common comment from experts was that the virtual shadow would be more comfortable and decreased mental workload, because of an effect of the information density (minimal number of graphics) and appropriate timing. The positive effects of the size, position, and color were that the growth and movement of the shadow would catch the driver's attention and help with perception. Experts expected that there could be potential issues from some of the current design factors, such as the shape. The shape and the length of tether could be an issue if the driver cannot tell which pedestrian a tether is attached to.

5.4 Discussion

The usability evaluation revealed that the virtual shadow would likely improve driver performance at each stage of cognitive processing. Regarding driver attention, results suggest that the bounding box would guide driver attention to pedestrians but then distract drivers from other critical environmental elements by narrowing their attention. This finding resonates with the well-known tradeoff between cost (worse divided attention) and benefit (better selective attention) of attention guidance (C. D. Wickens et al., 2015, p. 62) and one of the most challenging issues in AR applications (e.g., highlighting lane markers reduced pedestrian detection at nighttime driving, Sharfi & Shinar, 2014). Conversely, the virtual shadow is expected to achieve these two contradicting goals by cueing only pedestrians who is expected to intrude the vehicle's path. Regarding driver situation awareness, the virtual shadow expected to help drivers identify dangerous pedestrians and predict their movements for appropriate decision and response. With bounding boxes, drivers would need to filter out dangerous pedestrians among the clutter and predict their movement based on drivers' experience or expertise.

More importantly, the novel design metaphor would allow drivers to accurately predict possible collisions by visualizing the invisible mechanism of collision (see equation in Figure 4.1 in Chapter 4) in the form of a familiar shadow metaphor. Moreover, drivers could do so by relying on lower level perceptual process rather than high level analytic mental computation (possibility of shortcuts in the driver's cognitive process, Figure 3.4 in Chapter 3). Therefore, more attentional resources may be reserved for drivers to deploy their attention broadly across other environmental elements that might be critical or important in a given driving context. As such, the virtual shadow balances cost and benefit of attentional guidance which agrees with previous findings about the benefit of configural displays and emergent features (Bennett & Flach, 2011, p. 194).

6. Empirical Usability Evaluation in a Driving Simulator

6.1 Objective

The analytic usability evaluation predicted positive consequences of the virtual shadow on the driver cognitive process (see Chapter 5). This experiment aimed to examine if similar predicted benefits of the virtual shadow are observed in an empirical user study. To be specific, this experimental user study sought to answer (RQ5): What are the effects of AR pedestrian collision warnings (PCW) on driver situation awareness (SA) and workload? Regarding SA, we were particularly interested in (1) whether AR warnings improve driver SA about pedestrians (which was the purpose of the driver interface design) and (2) what are consequences of AR warnings on driver SA about other environmental elements such as other vehicles, landmarks, traffic signs and signals which are not augmented by warning interfaces but still critical for safe driving. We also examined drivers' confidence in their SA that might be important in determining their consequent actions (such as either initiating appropriate reactions or delaying reactions to seek more evidence about a situation).

6.2 Method

To better investigate the driver's cognitive process, we used a driving simulator that allowed us to control driving scenarios and tasks without actual threats to human subjects. Augmented natural driving footage was projected in front of a real car cab which is the same as the method used in the analytic usability evaluation. Participants were asked to mimic driving while experiencing different types of AR pedestrian collision warning interfaces. Driver SA was directly measured by a query-based method, namely the situation awareness global assessment technique (SAGAT, Endsley, 1988, 2012). Participants' subjective ratings on confidence in their own SA and workload (NASA-TLX, Hart, 2006) were also collected.

6.2.1 Participants

A total of 24 gender-balanced undergraduate students at Virginia Tech with normal or corrected-to-normal vision participated in the study. On average, they were 21.4 years old (SD = 3.1) with 4.7 years driving experience (SD = 2.9) and drove 4.5 hours (SD = 2.6) per week.

6.2.2 Apparatus

Augmented Video. The same bounding box and the virtual shadow design metaphors for AR PCW used in the analytic usability evaluation (Figure 5.1 in Chapter 5), were prototyped with various natural driving scenarios using the augmented video technique (Soro et al., 2014). We populated each PCW interface design for all driving scenarios to provide each participant with different combinations of warning interface and driving scenario to reduce expectancy and learning effects.

Driving simulator. The same driving simulator used for the analytic usability evaluation was used (Figure 5.3 in Chapter5) for this user study.

6.2.3 Procedure

The experimental user study consisted of four sessions: (1) introduction and pre-test survey, (2) a practice trial, (3) experimental trials, and (4) a post-test interview. Upon arriving to the driving simulation room in COGENT laboratory at Virginia Tech, participants were asked to read and sign the study's informed consent form (see Appendix B for IRB approval and C for informed consent form). An experimenter explained the purpose and overall procedure of the study. Participants were asked to fill out a survey form about their demographic information and driving experience (Appendix D). In a practice trial, an experimenter gave an in-car orientation to explain details about the simulator and participants' tasks. One practice trial was given without any measurement to have participants get familiar with the driving simulator and the procedure. In experimental trials, each participant had three driving trials. They were asked to mimic driving to perform wayfinding tasks, while using different PCW interface designs. During each driving trial, the simulator was paused at four random time points and the experimenter asked questions

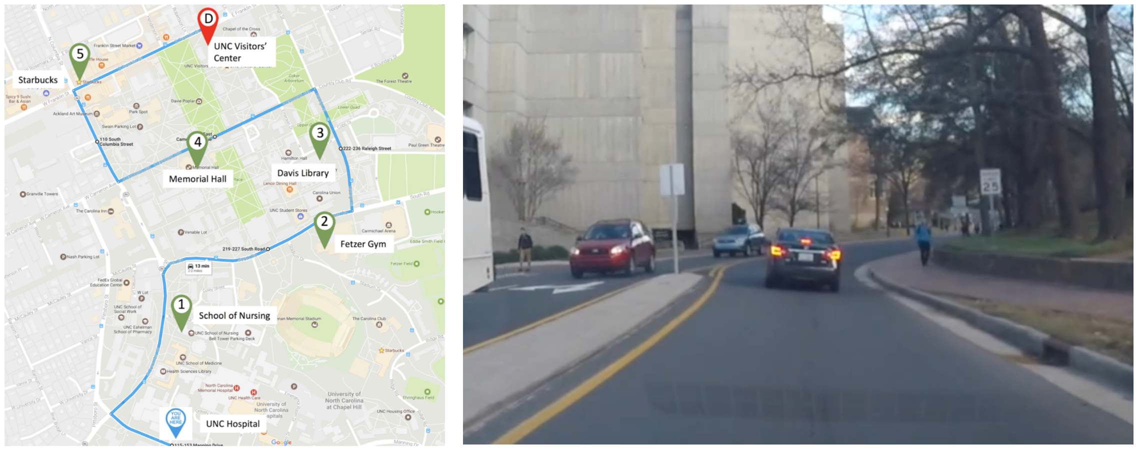

Figure 6.1 A naturalistic driving scenario and route plan
An example of a route plan (left) of a natural driving scenario recorded at University of North Carolina, Chapel Hill, NC. The scenario includes road events such as pedestrian crossing, changing traffic lights, changing speed limits and a braking lead vehicle (right).

about situations and confidence levels on participants' answers. After participants completing each trial, they were asked to fill out a NASA-TLX form. After completing all driving trials, participants moved to a post-test room and were gave comments on their experience (Appendix H). The experiment took about an hour per participant.

6.2.4 Driving Scenario and Participants' Tasks

We gave participants three real driving scenarios recorded at University of North Carolina, Chapel Hill, NC to avoid possible bias from locally-recruited participants' (who were living in or nearby Blacksburg Virginia) familiarity with the geographical area that might bias their situation awareness. Each driving footage was about 10 minutes long and included similar (in terms of road complexity and amount of road events) but different scenarios (in terms of specific route and road events). Figure 6.1 shows an example of a pre-defined route used for a driving scenario that includes various road events such as pedestrian crossings, changing traffic lights, changing speed limits and braking lead vehicles. Participants were asked to mimic driving (see Chapter 5 for details) to follow pre-defined routes to get to the destinations (see Appendix G for all route plans for driving scenarios). Route plans were shown to the participants before their starting each trail and

Aα	Bγ	Cβ
Bβ	Cα	Aγ
Cγ	Aβ	Bα

Figure 6.2 Orthogonal Latin square
An example of a 3 X 3 orthogonal Latin square. D = {A, B, C} represents three different warning interface designs and S = {α, β, γ} represents three different driving scenarios. Each participant experienced 3 ordered pairs from W and S, such that each participant saw each warning interface and driving scenario exactly once.

sat-nav style turn-by-turn voice instructions were given via pre-recorded audio that matched with each driving scenario.

6.2.5 Experimental Design

We conducted a one-way repeated measure experiment where each participant experienced all experimental conditions that consisted of three different PCW interfaces while driving. The order of pairs of warning interface and driving scenario was counterbalanced by 3 x 3 orthogonal Latin squares (also known as Graeco-Latin square, see Appendix D for details and Martin & Nadarajah, 2007) to minimize learning effects. Therefore, each participant saw all three warning interfaces paired with three different driving scenarios.

Visual warning (no warning, bounding box, virtual shadow): within-subject factor. In mediated interaction between humans and the environment, the specificity of interface representation (how well an interface represents the reality of a situation) can affect the user's belief about the situation (Bennett & Flach, 2011, p. 112). To examine this, we used three different interface designs that have different degree of specificity. The *control condition* (with no warning) does not specify anything about the situation which aims to measure participants' performance without any AR aid. *Bounding boxes* highlighted all detected pedestrians based on currently available pedestrian detection systems and

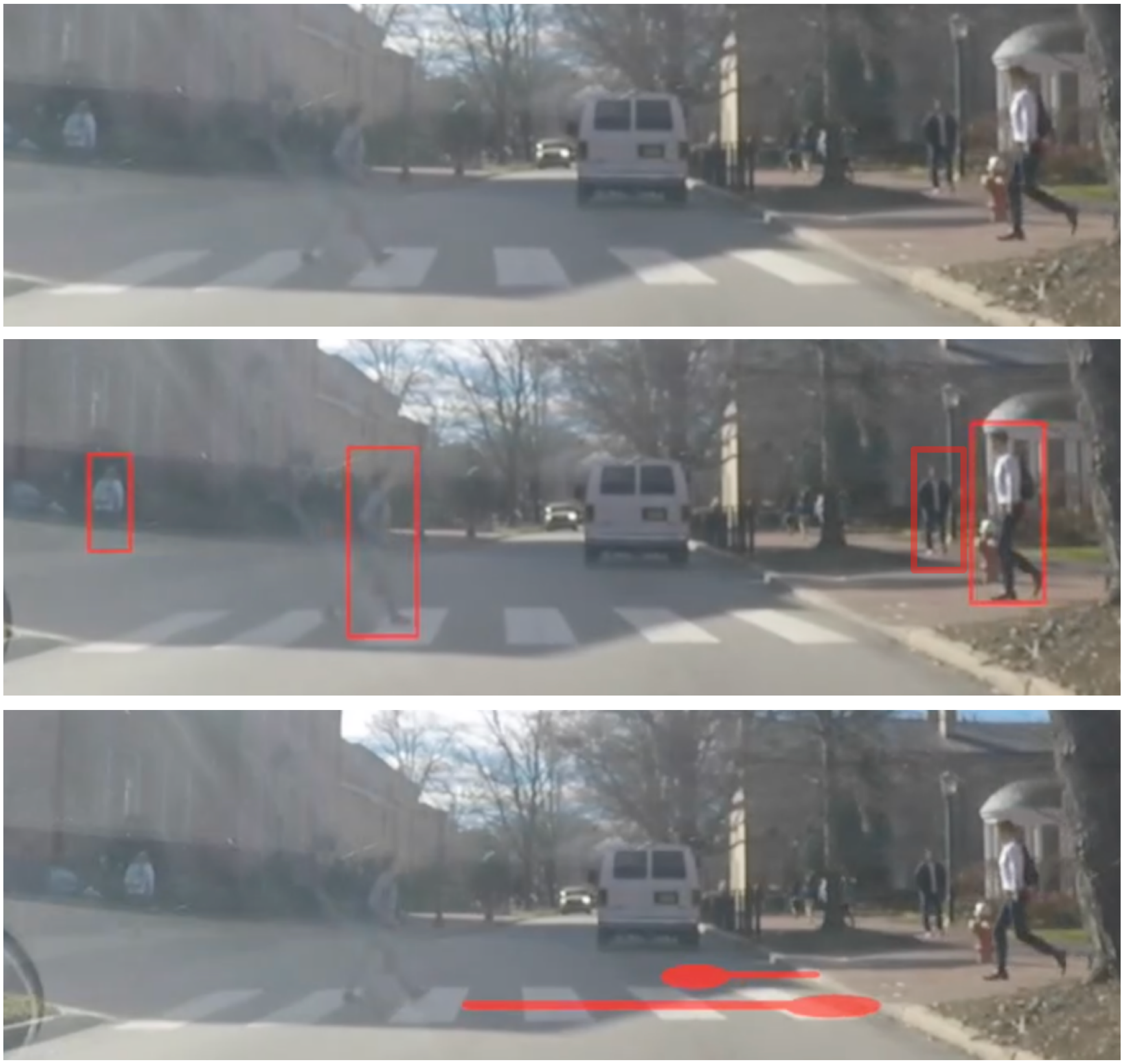

Figure 6.3 Visual warnings prototyped for the driving simulator study
The no warning condition (top, control condition) does not specify anything about the situation, bounding boxes (middle) highlight detected pedestrians and virtual shadows (bottom) visualize the dynamics of spatial intrusion (changing over time) by the approaching pedestrians.

algorithms (Benenson et al., 2014). *Virtual shadows* specified the predicted locations of collision with approaching pedestrians (Figure 6.3).

6.2.6 Measures

Accuracy of situation awareness. Driver SA was measured by a widely accepted probe-based method, situation awareness global assessment technique (for details, see a review from Salmon, Stanton, Walker, & Jenkins, 2009, pp. 36-56) with some operational improvements. SA queries were developed from a goal directed task analysis (GDTA) which hierarchically identified the driver's (1) goals, (2) decisions to be made to achieve each goal, and (3) required information for making each decision. SA questions specific to each driving context were then developed based on the information requirements. Therefore, all SA questions were relevant to situations that the drivers need to be aware of for safe transportation which is the functional purpose of the system identified in our work domain analysis (WDA) as well. Consequently, we did not ask questions such as "what is the color of the vehicle behind your car?" (Ma & Kaber, 2007), which some at face value one might consider a measure of SA but are not relevant to safe driving. The outcomes from GDTA (see Appendix F for details) and SA queries (see Appendix G for examples) were reviewed by four subject matter experts (SMEs, 2 experienced drivers and 2 professional test drivers) to ensure validity of the content.

The first operational improvement we made was to employ a *perceptual matching technique*. To objectively and directly measure SA, SAGAT asks questions about a dynamic situation relevant to the operator's on going tasks while blacking out the task scenarios unexpectedly so that the operators need to answer the SA questions using only their working memory. The operators' answers are then objectively evaluated based on the ground truth of the situation. However, some researchers have criticized this technique arguing that SAGAT is solely a test of visual memory capacity in front of a blank screen (Durso, Dattel, Banbury, & Tremblay, 2004). To help mitigate this drawback and improve the querying procedure, we paused driving scenarios, presented the exactly same driving scenes but without specific road events present, and asked participants to perceptually match locations of specific road events experienced during the trial with pre-defined zones of interests. For example, instead of asking the exact location (distance and direction) of an approaching vehicle (Figure 6.4 top) in front of a blank screen (Figure 6.4 middle), we presented the same scene without road events and asked participants to select zones of interest in the scene (Figure 6.4 bottom). With the perceptual matching technique, we aimed to improve the process of probing about dynamic situations to better measure driver SA.

Figure 6.4 The 1st operational improvement on SAGAT, perceptual matching
When a driving scenario pauses (top), instead of blacking out the scene (middle – traditional SAGAT), we showed the same scene without road events in the driving simulator's large screen and ask participants to select zones of interest (bottom – the proposed perceptual matching technique).

The second operational improvement we made was to ask questions about not only environmental elements cued by AR interfaces (i.e., pedestrians) but also other critical elements that are not augmented by interfaces. In doing so, we aimed to evaluate both probable positive (i.e., achieving the design intention of the driver interface) and negative (i.e., any unintended side effects) consequences of AR warning interfaces on driver SA. For this purpose, we classified all SA queries into four groups by different types of environmental constraints identified from WDA (see Chapter 3 for details);

- G1 pedestrians,
- G2 moving obstacles such as other vehicles,
- G3 stationary obstacles including road geometry and landmarks, and,
- G4 legal obstacles such as traffic sings and signals.

During the experimental user study, we paused each driving scenario four times and at each pause asked questions about a selected environmental element such that SA queries in a scenario covered all four types of environmental constraints. In fact, this is an effort to measure driver SA about the entire demand of a given situation, reflecting one of the implications from WDA (see section 3.4 for details). Participants could not predict when the scenario would pause and what environmental elements would be queried. It is also important to note that we paused driving scenarios when AR warnings were presented so that we could evaluate effects of AR PCW on driver SA; not only about pedestrians but also about other relevant elements in the scenario. Furthermore, at each pause, we asked 3 questions about a selected environmental element to measure the driver's level of SA (L1

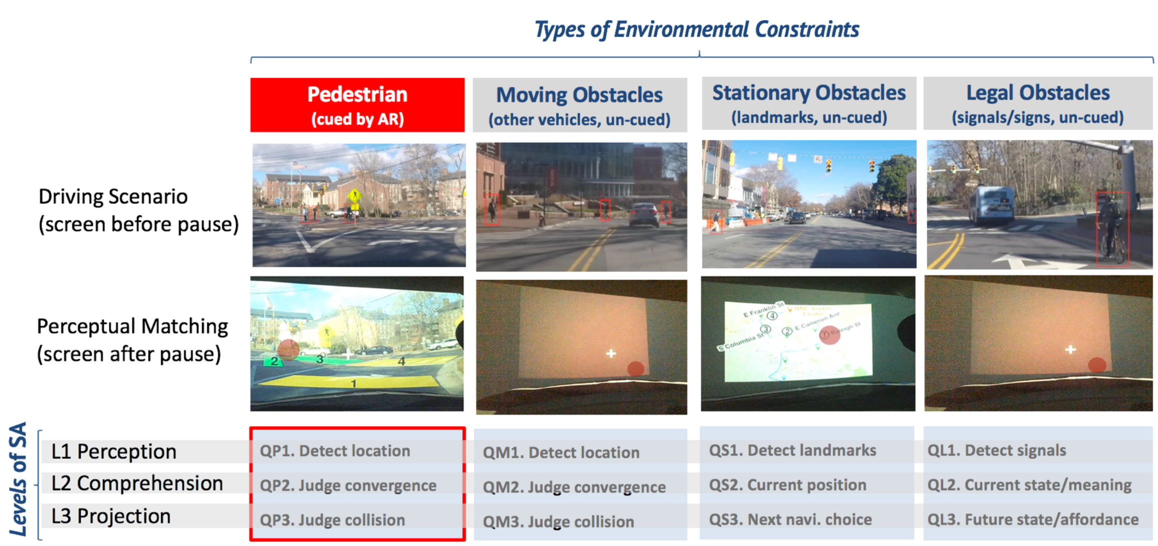

Figure 6.5 The 2nd operational improvement on SAGAT.
For each driving trial a total of 12 questions were asked to assess both breadth (4 *types of environmental constraints* relevant to safe driving) and depth (3 *levels of SA*) of the driver's knowledge about situations. Driving scenarios unexpectedly paused after AR warning was presented. At each pause, the driver was asked to answer 3 questions about a selected environmental element (among four types of environmental constraints) which were presented by the perceptual matching technique.

perception, L2 comprehension, L3 projection; Endsley, 2012) which correspond with the driver's state of knowledge at each stage of his / her cognitive process, reflecting one of the implications from control task analysis (CTA, see section 3.4 for details). In sum, we asked 12 SA questions (about 4 *types of environmental constraints* × 3 *levels of SA*) per driving scenario (Figure 6.5). With these operational improvements, we aimed to evaluate both the breadth and depth of the driver's knowledge about the dynamic environment and the impact of different AR PCW interface designs on SA.

After data collection, the accuracy of each answer to a given SA query was evaluated based on the ground truth of the driving scenario. The objective measure for accuracy of SA (i.e., the SAGAT score) was coded as a binary score (correct or incorrect) for each answer.

Confidence and overconfidence bias in situation awareness. Participants were asked to rate their confidence on each answer to SA queries right after answering the SA question. Confidence ratings were then coded on a binary scale (high or low). A score for overconfidence bias was then assigned by relating the participant's subjective confidence and objective accuracy of SA such that high confidences on incorrect answers were considered as overconfident (Sulistyawati, Wickens, & Chui, 2011).

Workload. Driver workload was measured by NASA Task Load Index (NASA-TLX) which is a subjective, multidimensional assessment tool developed by NASA (Hart & Staveland, 1988). It considers six dimensions of workload including subjective ratings on overall performance, frustration, effort, mental, physical, and temporal demand of a task. We used a simplified version of TLX, a Raw TLX (RTLX) which eliminates pairwise comparisons and weighting processes among dimensions, because RTLX was found to be equally sensitive to the original version in general (Hart, 2006).

6.2.7 Data Analysis

To examine the effects of AR PCW on binary measures of driver responses (i.e., SA and overconfidence scores), we performed Cochran's Q tests (Conover, 1980), which are non-parametric alternatives to the one-way repeated measures ANOVA for binary data. We also conducted Friedman tests (Conover, 1980) on workload measures which are non-

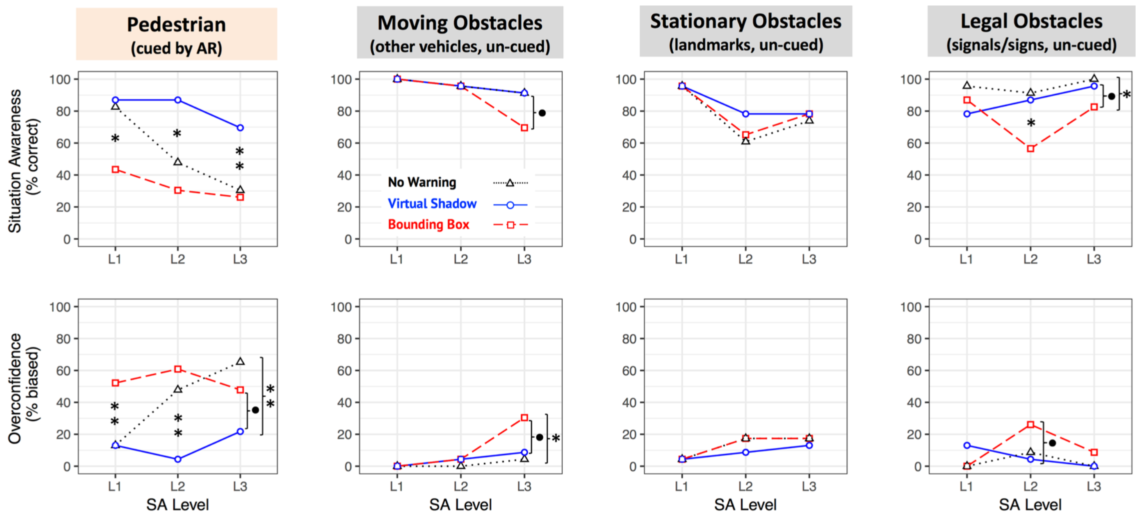

Figure 6.6 Effects of visual warning on driver SA and overconfidence.
Mean percentage of correct answers are reported as SA performance index which are decomposed into 3 levels (L1 perception, L2 comprehension, and L3 projection) of SA about 4 types of environmental constraints. Mean percentage of overconfidence bias are reported by the corresponding SA components. The significance of differences between experimental conditions are indicated by *'**' $p < 0.01$*, *'*' $p < 0.05$*, '•' *$p < 0.1$* based on the results from post-hoc McNemar tests.

parametric alternatives for ordinal data, since participants' TLX responses were not normally distributed. Whenever we found significant main effect, we performed post-hoc McNemar tests (Mangiafico, 2016b), which are non-parametric alternatives to paired t-tests, for pair-wise comparisons among experimental conditions on the binary data with false discovery rate adjustment (Bretz, Hothorn, & Westfall, 2016) on *p-values* to account for multiple comparisons.

6.3 Results

We analyzed the data from 23 participants excluding a participant who experienced strong motion sickness in the driving simulator. For the binary response of SA and overconfidence scores, the mean percentage of correct responses (proportion of correct answers to the total number of questions asked in each category) and the mean percentage of overconfident SA are reported as the final performance index. Figure 6.6 visualizes driver SA and overconfidence scores in each experimental condition.

6.3.1 Driver Situation Awareness

The descriptive statistics of SA scores (mean proportion of the correct answers with Clopper-Pearson binomial confidence intervals (Mangiafico, 2016b; Newcombe, 1998) for each PCW condition) are reported in Table 6.1. Cochran's Q tests revealed significant effects of visual warnings on driver SA about pedestrians (L1, L2, and L3) and legal obstacles (L2 and L3). The effect on SA about moving obstacles (L3) were marginal. No significant effect was found on SA about stationary obstacles.

Regarding pedestrians, drivers answered correctly to SA questions about their perception of pedestrians (SA level 1) 86.96% of the time with the virtual shadow, 82.61% with no warning, and 43.48% with the bounding box. A Cochran's Q test revealed these differences were statistically significant $Q(2,23) = 10.706, p = 0.005$ and post-hoc McNemar tests found significant differences between the bounding box condition and other conditions ($p = 0.008$ as compared to the virtual shadow and $p = 0.019$ as compared to the no warning condition). Drivers correctly identified pedestrians who were heading into the vehicle's path (SA level 2) 86.96% of the time in the virtual shadow condition, 47.83% in the no

Table 6.1 Descriptive statistics for participants' SA scores
Mean proportion (%) of the correct answers are reported with 95% Clopper-Pearson binomial confidence intervals; *proportion correct* [*lower limit*, *upper limit*]. L1: 1st level of SA (perception), L2: 2nd level of SA (comprehension) and L3: 3rd level of SA (projection)

Env. Elements \ Warning		No Warning	Bounding Box	Virtual Shadow
Pedestrian	L1	82.61 [61.22, 95.05]	43.48 [23.19, 65.51]	86.96 [66.41, 97.22]
	L2	47.83 [26.82, 69.41]	30.43 [13.21, 52.92]	86.96 [66.41, 97.22]
	L3	30.43 [13.21, 52.92]	26.09 [10.23, 48.41]	69.57 [47.08, 86.79]
Moving Obstacles	L1	100.00 [85.18, 100.00]	100.00 [85.18, 100.00]	100.00 [85.18, 100.00]
	L2	95.65 [78.05, 99.89]	95.65 [78.05, 99.89]	95.65 [78.05, 99.89]
	L3	91.30 [71.96, 98.93]	69.57 [47.08, 86.79]	91.30 [71.96, 98.93]
Stationary Obstacles	L1	95.65 [78.05, 99.89]	95.65 [78.05, 99.89]	95.65 [78.05, 99.89]
	L2	60.87 [38.54, 80.29]	65.22 [42.73, 83.62]	78.26 [56.30, 92.54]
	L3	73.91 [51.59, 89.77]	78.26 [56.3, 92.54]	78.26 [56.30, 92.54]
Legal Obstacles	L1	95.65 [78.05, 99.89]	86.96 [66.41, 97.22]	78.26 [56.30, 92.54]
	L2	91.30 [71.96, 98.93]	56.52 [34.49, 76.81]	86.96 [66.41, 97.22]
	L3	100.00 [85.18, 100.00]	82.61 [61.22, 95.05]	95.65 [78.05, 99.89]

warning condition and 30.43% in the bounding box condition. These differences were statistically significant (Cochran's $Q(2,23) = 12.667$, $p = 0.002$). In particular, the virtual shadow condition was associated with higher SA as compared to both the no warning condition and bounding box conditions. Participants made correct responses on the level 3 SA questions predicting possible collisions 69.57% of the time with the virtual shadow, 30.43% with no warning, and 26.09% with the bounding box. These differences were also statistically significant (Cochran's $Q(2,23) = 10.111$, $p = 0.006$). Post-hoc McNemar tests showed higher driver SA with the virtual shadow than with other visual warnings ($p = 0.007$ as compared to the no warning condition and $p = 0.008$ as compared to the bounding box condition).

Regarding moving obstacles, participants correctly predicted (SA level 3) other vehicles' relative movement (e.g., whether the headway from a lead vehicle was decreasing or not) 91.30% of the time in both the no warning condition and the virtual shadow condition and 69.57% in the bounding box condition. However, the effects of visual warnings on participants' SA about moving obstacles were marginal (Cochran's $Q(2,23) = 65.329$, $p = 0.07$).

No statistically significant difference was found in participants' SA about stationary obstacles (e.g., landmarks indicate current location of the car or upcoming navigational choices) among different visual warning conditions.

Regarding legal obstacles such as traffic lights and signs, drivers correctly perceived (SA level 1) those obstacles 95.65% of the time in the no warning condition, 86.96% in the bounding box condition, and 78.26% in the virtual shadow condition. These differences were not statistically significant. Participants correctly understood (SA level 2) consequences of the perceived signs (e.g., whether they were speeding or not when a speed limit sign was visible) 91.30% of the time in the no warning condition, 86.96% with the virtual shadow, and 56.52% with the bounding box (Cochran's $Q(2,23) = 8.143$, $p = 0.017$). Post-hoc comparisons showed lower driver SA in the bounding box condition as compared to other conditions ($p = 0.01$ as compared to the no warning condition and $p = 0.05$ as compared to the virtual shadow condition). Participants' responses on the level 3 SA questions varied by visual warnings with 100% correct answers in the no warning condition, 95.65% in the virtual shadow condition and 82.61% in the bounding box condition (Cochran's *Q(2,23) = 6.5, p = 0.039*). Difference between the no warning condition and the bounding box condition was statistically significant (*p = 0.046*).

6.3.2 Overconfidence in Situation Awareness

The descriptive statistics of overconfidence scores (mean proportion of the overconfident SA with Clopper-Pearson binomial confidence intervals for each PCW condition) are reported in Table 6.2. Cochran's Q tests revealed significant effects of visual warnings on driver overconfidence about pedestrians (L1, L2, and L3) and moving obstacles (L3). The effect on SA about legal obstacles (L2) were marginal. No significant effect was found on SA about stationary obstacles.

There were significant effects on driver overconfidence in their SA about pedestrians across the three visual warning conditions. Cochran's *Q(2,23) = 10.800, p = 0.005* for perception, *Q(2,23) = 14.632, p = 0.001* for comprehension, and *Q(2,23) = 8.941, p = 0.011* for projection. Participants showed overconfidence on their perception of pedestrians

Table 6.2 Descriptive statistics for participants' overconfidence in their SA
Mean proportion (%) of the overconfident SA are reported with 95% Clopper-Pearson binomial confidence intervals; *proportion biased* [*lower limit*, *upper limit*]. L1: 1st level of SA (perception), L2: 2nd level of SA (comprehension) and L3: 3rd level of SA (projection)

Env. Elements \ Warning		No Warning	Bounding Box	Virtual Shadow
Pedestrian	L1	13.04 [2.78, 33.59]	52.17 [30.59, 73.18]	13.04 [2.78, 33.59]
	L2	47.83 [26.82, 69.41]	60.87 [38.54, 80.29]	4.35 [0.11, 21.95]
	L3	65.22 [42.73, 83.62]	47.83 [26.82, 69.41]	21.74 [7.46, 43.70]
Moving Obstacles	L1	0.00 [0.00, 14.82]	0.00 [0.00, 14.82]	0.00 [0.00, 14.82]
	L2	0.00 [0.00, 14.82]	4.35 [0.11, 21.95]	4.35 [0.11, 21.95]
	L3	4.35 [0.11, 21.95]	30.43 [13.21, 52.92]	8.70 [1.07, 28.04]
Stationary Obstacles	L1	4.35 [0.11, 21.95]	4.35 [0.11, 21.95]	4.35 [0.11, 21.95]
	L2	17.39 [4.95, 38.78]	17.39 [4.95, 38.78]	8.70 [1.07, 28.04]
	L3	17.39 [4.95, 38.78]	17.39 [4.95, 38.78]	13.04 [2.78, 33.59]
Legal Obstacles	L1	0.00 [0.00, 14.82]	0.00 [0.00, 14.82]	13.04 [2.78, 33.59]
	L2	8.70 [1.07, 28.04]	26.09 [10.23, 48.41]	4.35 [0.11, 21.95]
	L3	0.00 [0.00, 14.82]	8.70 [1.07, 28.04]	0.00 [0.00, 14.82]

(SA level 1) 52.17% of the time with the bounding box, 13.04% of the time with both the virtual shadow and no warning. Participants were also overconfident in their ability to identify merging pedestrians among others 60.87% of the time with the bounding box, 47.83% in the no warning condition and 4.35% with the virtual shadow. In predicting possible collisions with pedestrians (if no corrective action would be taken), participants were overconfident 65.22% of the time without warning, 47.83% with the bounding box and 21.74% with the virtual shadow. The virtual shadow significantly reduced participants' overconfidence in comprehension ($p = 0.004$) and projection ($p = 0.004$) while the bounding box even increased overconfidence in perception of pedestrians ($p = 0.007$), as compared to the no warning condition.

Visual warnings had significant effects on participants' overconfidence in their prediction of other vehicles' relative movement (SA level 3); Cochran's $Q(2,23) = 6.200, p = 0.045$. Specifically, participants were also overconfident in their SA 30.43% of the time with the bounding box which was significantly higher ($p = 0.034$) as compared to 4.35% overconfidence in the no warning condition.

No effect of visual warnings on overconfidence bias was found in driver SA about stationary obstacles such as landmarks that indicate current location of the car or upcoming navigational choices.

Regarding legal obstacles, effects of visual warnings on participants' overconfidence in their comprehension of situations (e.g., identifying road signs that required driver reaction, SA level2) were marginal (Cochran's $Q(2,23) = 5.250, p = 0.072$).

6.3.3 Workload

No effects of visual warnings on participants' workload was found (Friedman's $\chi^2(2) = 2.782$, $p\text{-value} = 0.249$). The reported median TLX scores (out of 100) were 40.0 [35.0, 46.7] in the no warning condition, 46.7 [38.3, 50.0] in the bounding box condition and 45.0 [36.7, 48.3] in the virtual shadow condition. Numbers inside the brackets indicate lower and upper limits of 95% confidence intervals for the median of the Likert data (for details about descriptive statistics for Likert data, see (Mangiafico, 2016a). Friedman's tests on all six subscales of the TLX also found no effect of visual warnings.

6.4. Discussion

The key findings from the empirical usability evaluation are that (1) the virtual shadow improved participants' SA and reduced overconfidence about pedestrians, while not affecting their SA about other environmental elements not augmented by the AR HUD, (2) the bounding box degraded participants' SA about not only pedestrians but also other un-cued environmental elements, and (3) AR warnings did not affect participants' subjective workload. We further compared these results with those expected by expert evaluators in the analytic usability evaluation and discuss possible reasons for these observations. We also discuss positive and negative consequences of visual warnings on driver SA and their implications for AR driver interface design, followed by limitations of the study.

As expected in the analytic usability evaluation, the virtual shadow resulted in improved driver SA about pedestrians while the bounding box did not help with driver SA about pedestrians (as compared to the no warning condition). Since participants were aware of nearby pedestrians (SA level 1) correctly even without warnings (82.61% of the time in the control condition), the effects of AR PCW on driver perception of pedestrians (SA level1) were not significant. However, the virtual shadow helped drivers further identify (SA level 2) potentially dangerous pedestrians (who's trajectories were converging to the vehicle's path) among the many pedestrians within the driver's view. The virtual shadow also improved participants' prediction (SA level 3) of pedestrians' movement relative to the driver's vehicle. The expectations from the heuristic evaluation were supported by this empirical evidence. On the contrary, participants found the bounding box unhelpful in their perception, comprehension and projection of pedestrians' movement. In fact, the bounding box even degraded participants' perception of pedestrians as compared to the no warning condition which was not predicted by the heuristic evaluation. The post-test interview with participants revealed that highlighting all detected pedestrians with red boxes was perceived as clutter and likely distracted participants from correctly perceiving the nearby pedestrians.

Contrary to expectations from the analytic usability evaluation, the empirical user study did not provide any evidence for reduced driver workload when AR warnings were given. This might be, in part, because the task itself was too easy (the subjective TLX score was 40 out of 100 in the no warning condition) for experienced drivers to perform, since collision avoidance can be achieved by learned, skill-based behavior (de Waard & Lewis-Evans, 2014). Patten et. al reported that expertise in driving skills allows drivers to better handle unexpected traffic situations with less workload (Patten, Kircher, Östlund, Nilsson, & Svenson, 2006). It is known that crash rates among novices are high and drop substantially over the first 2 years of driving with a noticeable drop during the first 6 months (Mayhew, Simpson, & Pak, 2003). A reported mean number of miles driven after licensure, increased and was flat around 415 miles per month (about 5000 miles per year; McCartt, Shabanova, & Leaf, 2003). Another possible reasons for this finding is that using only subjective mental workload measures might not be sensitive enough to detect differences when the operators perform the same task with slightly different HMIs (in terms of diagnosticity of measures, Angell et al., 2006; Mehler, Reimer, & Zec, 2012). Future work could include not only subjective but also objective measures for better understanding the effects of AR warnings on driver workload, as suggested by (Angell et al., 2006; de Waard & Lewis-Evans, 2014; De Waard & Studiecentrum, 1996).

More importantly, the empirical user study showed that AR interfaces can have both positive and negative consequences on driver SA depending upon how we design specific forms of graphical elements described in Chapter 4 (for details see 4.2.1 design factors of AR graphics). The virtual shadow achieved one of the explicit purposes of it's design (i.e., improve driver SA about pedestrian) while not affecting driver SA about other critical environmental elements. However, the bounding box showed negative side effects on driver SA such that it degraded driver SA about un-cued environmental elements. This suggests that poorly designed AR interfaces can cause cognitive distraction by degrading the user's situation awareness about other environmental elements which are not augmented by AR HUD interfaces.

The empirical usability evaluation also resulted in important findings which were not captured by the analytic evaluation. One interesting finding is the effects of AR PCW on driver overconfidence in their SA. In closed loop interactions between human and environment, the metacognition (e.g., the driver's belief about their own SA) plays a critical role (Sulistyawati et al., 2011). The driver's subjective confidence in his / her own SA will direct the consequent actions if the driver decides to seek more evidence about the situation or start acting on the environment (Endsley, 2012; Flach, 2015). Understanding drivers' overconfidence bias (i.e., relation between objective accuracy and subjective confidence of their own SA) is even more important, since the overconfidence bias might have significant consequences on driver safety and performance. If the driver has low confidence on actually poor SA (this is not considered to be overconfident SA), he / she might seek more evidence from the environment to improve SA. If the driver has a high confidence on actually high SA (this is not considered as overconfidence bias), he / she might initiate appropriate action on the environment. The most dangerous instances might happen when the driver is overconfident in his / her SA (high confidence on poor SA) which might result in critical safety or performance consequences such as incidents or accidents. This empirical usability evaluation revealed that the virtual shadow helped reduce driver overconfidence bias in own SA while the bounding box was found to be not be helpful in that regard as compared to the no warning condition.

Despite the aforementioned contributions of the proposed empirical evaluation methods, this work also has some limitations to generalize the findings to other situations. The proposed operational improvement on SAGAT could be problematic in field studies, since it still requires freezing in the task scenario. This problem has been reported by many researchers (Bolstad, Cuevas, Wang-Costello, Endsley, & Angell, 2008; Durso et al., 2004; Endsley, 2012) and might be attenuated to some extent by additional operational improvements such as querying when the car stopped in traffic or at a traffic signal as proposed by Sirkin, Martelaro, Johns, and Ju (2017).

Another limitation of the study is the high context dependency of SA queries which is one of inherit limitations from SAGAT. The developed set of queries (see Appendix G) need to be tailored or adapted for usability evaluation of other types of AR driver interface. For example, a usability evaluation of AR navigation aids might require a different set of pauses to capture appropriate driving context relevant to the task that AR driver interfaces aim to support (e.g., freezing driving scenario when the driver need to make a navigational choice at an intersection or a fork).

In sum, this work proposed a novel way of evaluating usability of automotive AR visual interfaces by examining their positive and negative consequences on driver situation awareness about both cued and un-cued environmental elements. We also proposed an operational improvement in SAGAT to (1) better fit AR use cases and usability evaluations and (2) better understand the effects of AR on both the breadth and depth of the driver's knowledge about the dynamic environment. Understanding both positive and negative consequences of AR interfaces can inform not only comparative evaluation among design alternatives but also assist in incrementally improving design iterations to better support drivers' information needs, situation awareness, and in turn, performance and safety.

7. Empirical Usability Evaluation in a Parking Lot

7.1 Objective

Driving is one of many promising tasks that can benefit from AR where conformal graphics integrated in the real world can accurately guide drivers' attention to relevant task related elements and potential hazards (Gabbard et al., 2014). Therefore, existing knowledge about human depth perception in AR can inform HUD interface design (see section 2.2.2 for more details). However, for optimal design of driver interfaces, there are still open questions such as; What are the most important or effective depth cues to ensure sufficient driver performance in AR? Do additional depth cues assist in guiding drivers' attention to hazards in the scene? And, do we need stereoscopic head-up displays in the car? As an initial attempt to address these questions, this work considered two extreme display conditions for pedestrian visual warnings (in terms of affordable depth cues by current display technologies for HUDs) and compared their effects on driver performance in a pedestrian hazard situation. A monoscopic display conveyed a set of perspective depth cues including linear perspective, relative size and height in the visual field, while a volumetric display delivered an additional set of depth cues including binocular disparity, convergence, motion parallax and accommodative focus. This work also aimed to answer practical questions regarding pedestrian collision warning (PCW) driver interface design; (RQ6) What are the effects of AR PCWs on driver behavior and performance? Can warnings with conformal graphics improve driver performance? What influences do these interfaces have on driver behavior? For this purpose, we examined driver performance gains and behavioral changes associated with conformal graphics, as compared to both one of current PCW driver interfaces, and, no warning scenarios (i.e., no PCW driver interface).

7.2 Method

To investigate the effects of depth cues afforded by AR HUDs on driver performance and behavior, we ran an experimental user study in a large parking lot where participants needed to manage the actual demands of driving in a controlled but realistic driving scenario. Participants drove a test vehicle while braking for cross traffic with assistant from

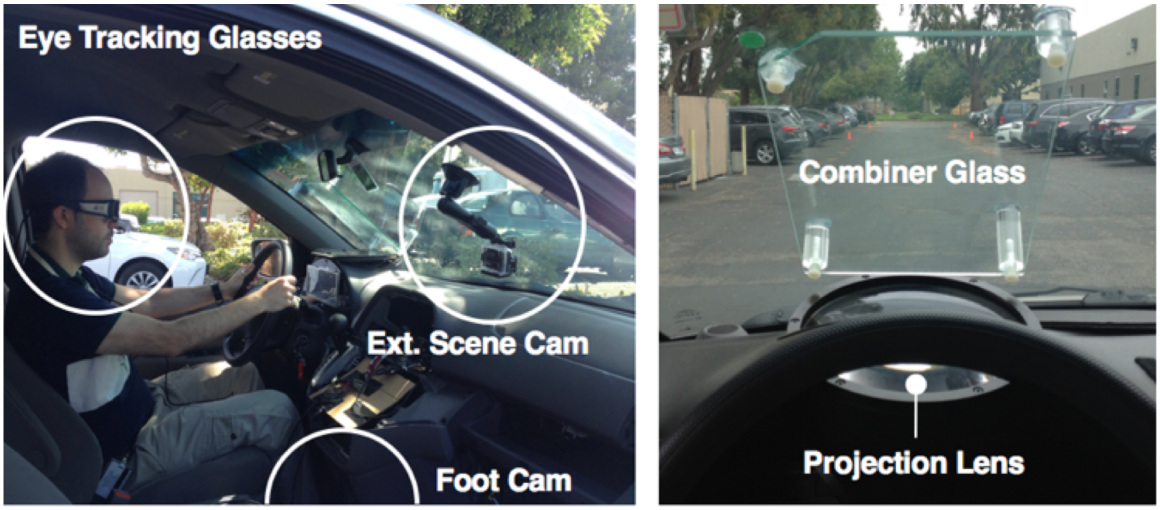

Figure 7.1 Test vehicle equipped with a HUD.
(a) The test vehicle equipped with a GPS, eye tracking glasses, cameras and (b) the in-vehicle volumetric head-up display

visual warnings on a HUD. Drivers' behavior and performance were recorded by eye tracking glasses, in-vehicle cameras and a global positioning system (GPS).

7.2.1 Participants

Sixteen licensed drivers with normal or corrected-to-normal vision participated in the study. On average, they had 23 years (SD=9) of driving experience and drove 11,200 miles (SD=4,854) per year. The range of age was between 31 to 55. Three participants had some minimal experience with head-worn AR (e.g., Google Glass), but none had experience in driving a car with AR HUDs.

7.2.2 Apparatus

Test vehicle. We equipped a 2009 Honda Odyssey test vehicle with various devices to record driver behavior and performance (Figure 7.1a). A high accuracy real-time kinematic GPS (OxTS RT4003 with smaller than *20cm* localization error) was used to record the test vehicle's position, velocity and acceleration at *200Hz*. Two cameras (GoPro Hero3+) recorded drivers' foot behavior and the external scene at *24Hz*. Eye tracking glasses (SMI ETG with *80°×60°* tracking range) recorded participants' gaze behavior at *30Hz*.

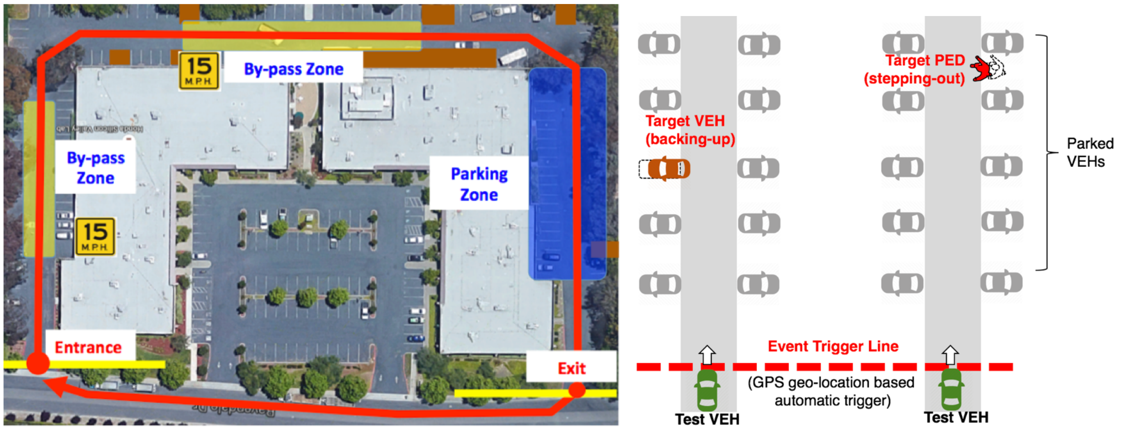

Figure 7.2 Parking lot and task scenario.
(a) A large parking lot (three sided *150m X 100m*) filled with parked vehicles, was used for the test site. Participants were asked to drive the test vehicle to find an available spot in the reserved parking zone. (b) Participants were asked to drive a constant speed of 15mph, and brake for any cross traffic such as backing-up vehicles or stepping-out pedestrians. Visual warnings on the HUD were automatically activated using real-time GPS and predefined geolocation of the trigger line.

Head-Up Display. In this experiment, the test vehicle also contained an in-vehicle prototype of an optical see-through HUD (Figure. 7.1b). It is a projection-based volumetric display with a swept-volume technique (Barry G Blundell, 2012) using fast switching image planes within a range of focal distance between *8m* and infinity (*0.125D ~ 0D*); affording flicker-free appearance of virtual objects in the 3D space with about *17°* circular field of view. This volumetric HUD is capable of providing not only perspective depth cues available in monocular displays but also additional depth cues such as binocular disparity, motion parallax, convergence and accommodation. Furthermore, by presenting AR graphics at the exact same focal distance as their real-world referents, observers are not forced to switch focus between virtual and physical objects. Therefore, it helps attenuate perceptual consequences (e.g., visual fatigue, discomfort and distorted depth perception) of incomplete or conflicting depth cues (Kruijff, Swan, & Feiner, 2010; Lambooij, Fortuin, Heynderickx, & IJsselsteijn, 2009; R. E. Patterson, 2015).

Parking lot. This experiment was conducted in a large three-sided parking lot (*150m* x *100m*, Figure 7.2a) which was filled with many parked vehicles to provide participants with a realistic driving environment. A one-way driveway passes through the parking area with a *15mph* speed limit. The parking lot consisted of three zones and one of them was designated for the participants to park the test vehicle as a part of an experimental scenario. It is noticeable that we chose the real roadway to better understand human performance in AR which cannot be replaced by driving simulators where most of real-world depth cues are confounded or not available.

7.2.3 Driving Tasks

For better ecological validity of the study, we gave participants a realistic parking lot scenario similar to their everyday life experiences. Participants were asked to drive in the parking lot to find an available spot within the reserved parking zone (Figure 2a). First, participants were asked to approach the entrance of the parking lot which was a starting line for each driving trial. They were asked to drive a constant speed of *15mph* (except during turns where they could slow down), until they arrived at the reserved parking zone. While driving, they were asked to brake for any cross traffic (e.g., backing-up vehicles or stepping-out pedestrians, Figure 2b). Participants were instructed not to swerve or detour but to make a complete stop for any cross traffic. No visual warnings were given in the control condition, while visual warnings on the HUD were given for experimental conditions. The driving task imposed actual driving demands (visual, cognitive and manual) on participants as they drove and reacted to real road events.

7.2.4 Procedure

The experimental user study consisted of four sessions; (1) pre-test survey, (2) practice trials, (3) experimental trials, and, (4) post-test interview. Upon participants' arriving at a preparation room, an experimenter introduced the study briefly and surveyed participants' demographic information and driving experience. Then, the experimenter guided participants to the test vehicle in the parking lot. During the practice session, participants were given an in-car orientation of the overall procedure and driving tasks. Eye tracking glasses were calibrated for each participant inside the test vehicle. Two practice trials were given without any measurement so that participants could get familiar with driving the test vehicle, the layout of the test site and the presence of AR HUD technology. In the experimental trials, participants were asked to drive the test vehicle to perform the parking task following a pre-defined route (the red line in Figure 7.2a). During the driving trials, an experimenter sat in the backseat and all traffic was controlled by experimenters. After completing all driving trials, participants gave comments on their experience. The experiment took about an hour for each participant.

We simulated V2X communication technology (Honda, 2014; Hussein et al., 2016; Olaverri-Monreal & Jizba, 2016) for vehicle and pedestrian localization in accordance with road events (i.e., backing-up vehicles and stepping-out pedestrians). For this purpose, we pre-defined the location of road events and associated trigger points. When the test vehicle passed trigger points, the experimenter sent signals to the backing-up vehicles or pedestrians via a walkie-talkie to activate the road events. These events were automatically transmitted to the HUD by the GPS to trigger visual warnings (Figure 7.2b). We sent signals to the pedestrian actor in advance to synchronize road events and warnings, considering the required time for the pedestrian's reaction based on our practice during pilot tests.

7.2.5 Experimental Design

A two-factor repeated measures experiment was conducted, where each participant experienced all experimental conditions; 4 levels of visual warnings and 2 levels of distance to the pedestrian. We counterbalanced the presentation order of experimental conditions to account for learning and ordering effects. To reduce drivers' anticipation of pedestrians, no-event trials were randomly added and the side of road events (left or right) was randomized. We also introduced backing-up vehicle events during the practice trials.

Visual Warning (no warning, current warning, monoscopic warning, volumetric warning): within-subject factor. The real-world pedestrian events, were augmented by visual warnings with four levels, which provided different sets of depth cues. In the control condition (i.e., no warning), the visual stimuli available to the driver were only those associated with the real pedestrians. In warning conditions, both a visual warning and a pedestrian appeared at the same time. The current warning interface condition was inspired by currently available PCW on the market. Specifically, a "BRAKE" indicator (text) was shown at the center of the HUD (Figure 7.3a), to notify drivers of the presence of a pedestrian in the vehicle's path. This cue contained no depth information about the real

Figure 7.3 Visual warnings presented on the HUD.
(a) The current warning condition shows "BRAKE" sign to inform the presence of pedestrian, and (b) the monoscopic and volumetric display conditions show a "virtual shadow" to inform the distance to and direction of an approaching pedestrian.

pedestrian. Both monoscopic and volumetric warning display conditions presented a virtual shadow, to inform drivers of the direction and distance to an approaching pedestrian using conformal graphics (Figure 7.3b). A virtual shadow is a dome-shaped conformal virtual object combined with a tether that appears on the ground at the location of the real pedestrian. The absolute size (diameter) of the dome was *1.0m* but it's apparent angular size from the driver's viewpoint varied between $2°$ and $8°$ depending upon the viewing distance as the driver moved (Figure 7.4). In the monoscopic display condition, the HUD presented the virtual shadow by a perspective projection of the 3D virtual object onto the nearest (*8m*) focal plane of the HUD. Therefore, it provided a set of perspective depth cues including linear perspective, relative size, and relative height in the visual field. Whereas

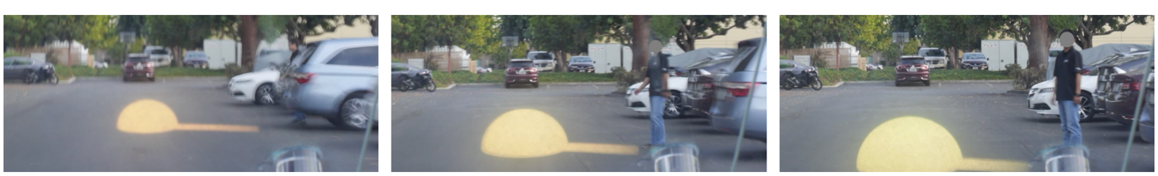

Figure 7.4 The virtual shadow in action presented on the AR HUD
The shadow is integrated in the real world based on the geolocation of the pedestrian (GPS coordinate) so that its apparent size and location (relative size and height in the driver's visual field) change as the driver approach the target pedestrian, similar to the real shadow of a pedestrian.

the volumetric display condition directly generated a 3D virtual object on the ground at the same distance as the pedestrian, providing a set of additional depth cues including binocular disparity, convergence, motion parallax, and accommodative focus.

Distance to Pedestrian (near, far): within-subject factor. The real-world road events happened at two different distances which might affect drivers' depth judgment and risk perception yielding different responses. The specific distances to the pedestrian were chosen to correspond with the time to collision (TTC); one of many critical factors that influences drivers' braking responses (Fitch et al., 2010). The near target pedestrians stepped out when TTC was 2.5 second (*16.7m* at *15mph*) which represents an urgent situation that might instigate last second hard braking responses (Fambro, Koppa, Picha, & Fitzpatrick, 2007; Fitch et al., 2010; Kiefer, LeBlanc, & Flannagan, 2005). The far target pedestrians appeared at 5.0 second TTC (*33.5m* at *15mph*) which represents a normal situation that might induce drivers' timed-normal braking responses.

7.2.6 Measures

Human behavior and performance in braking tasks can be evaluated by various measures that show the driver's capability of detecting, reacting to, and finally stopping apart from a road hazard. Measures can be either time-based (e.g., gaze reaction time, pedal reaction time and time to stop) or distance-based (e.g., perception, reaction, and stopping distance) (Fambro et al., 2007; Fitch et al., 2010; Kiefer et al., 2005; Langham & Moberly, 2010; Markkula, Benderius, Wolff, & Wahde, 2012). In this study, we used distance-based measures from the GPS log which was synchronized with eye tracking glasses and in-vehicle cameras. The distance-based measures allowed us to examine the process of braking as referenced to the initial distance gap to the pedestrian. All measures were corrected by an equation recommended by SAE J299 ("Stopping Distance Test Procedure," 2009) to account for discrepancy between actual and the target speed of the test vehicle (i.e., *15mph* for this experiment).

$$d_{corrected} = d_{measured} \times ({v_{target}}^2 / {v_{actual}}^2)$$

where, $d_{corrected}$ = corrected value of dependent variable, $d_{measured}$ = measured value of dependent variable, v_{target} = target entrance speed, v_{actual} = actual entrance speed.

Driver gaze and foot behavior. We analyzed drivers' gaze and foot video, timestamping drivers' behavioral events to obtain corresponding distance-based measures from synchronized GPS logs. Driver behavior was evaluated by four dependent variables: (1) *gaze-on visual warning*, (2) *gaze-on pedestrian*, (3) *foot-off accelerator pedal*, and, (4) *foot-on brake pedal*. Each dependent measure was calculated as distance (in meters) between the trigger point and corresponding location in which the event occurred (e.g., foot off accelerator pedal represents the distance travelled between the trigger point and the moment in which a driver took their foot off the accelerator pedal). By considering aforementioned four measures together, we also defined a categorical dependent variable, (5) *behavioral pattern*, based on the sequence of drivers' discrete actions that characterize drivers' overall response behavior.

Additionally, drivers' gaze behavior was classified into fixations, saccades and smooth pursuits (for more details, see Kasneci, Kasneci, Kübler, & Rosenstiel, 2015). In a driving context, smooth pursuits are important measures to address because all objects in driving scenes (even stationary objects) are continuously moving from the driver's moving viewpoint. Therefore, for the remainder of this paper, we will refer to gaze on objects as the smooth pursuit of objects. Since most gaze analysis software on the market do not

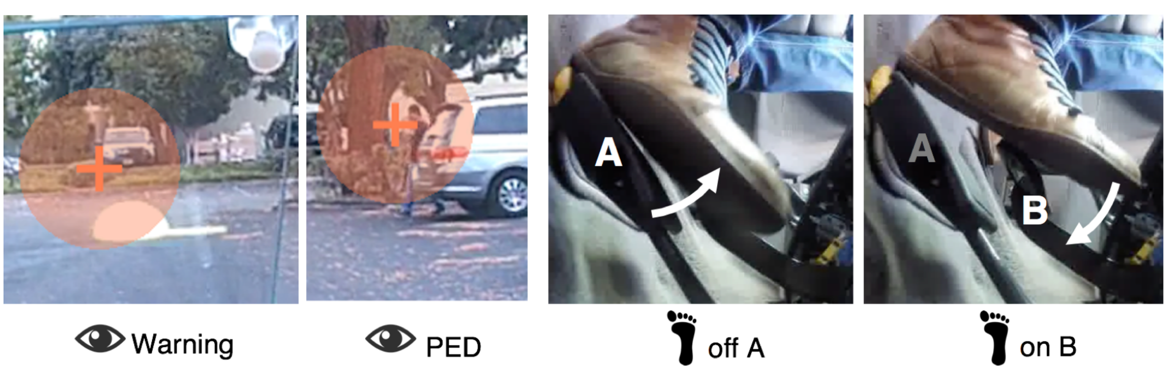

Figure 7.5 Driver gaze and foot behavior
Drivers (a) gaze behavior and (b) foot behaviors are analyzed to capture critical events including gaze-on warning, gaze-on pedestrian, foot-off accelerator pedal, and foot-on brake pedal.

support automatic analysis of smooth pursuits, we manually identified smooth pursuits based on a set of criteria. Specifically, we set threshold values on the location and time duration for a gaze to be considered a smooth pursuit. For the location threshold, we used the circular area within the radius of *2.5°* around each gaze point to represent human foveal vision (Strasburger, Rentschler, & Jüttner, 2011). For the duration threshold, *120 ms* was used which is the same threshold used in standard eye tracking software systems (e.g., SMI ETG) use to identify fixations (SMI, 2014). With these thresholds in place, we identified the set of gaze on visual warning and gaze on pedestrian events that occurred when drivers' gaze resided on the area around the AR visual warnings and actual pedestrians, respectively (Figure 7.5a).

Processing and coding video of drivers' footwell allowed us to determine when drivers' pedal maneuvers began and ended. Foot-off accelerator pedal response was timestamped when drivers' lifted their foot off the accelerator pedal, while foot-on brake pedal response was timestamped when drivers started pressing the brake pedal (Figure 7.5b).

As mentioned, we classified behavioral patterns by the sequence of drivers' responses. For example, pattern A was defined as a series of the following driver reactions: gaze-on warning followed by gaze-on pedestrian, foot-off accelerator pedal, then foot-on brake pedal. Pattern B was defined as: gaze-on warning followed by foot-off accelerator pedal, gaze-on pedestrian, then foot-on brake pedal. Pattern C was defined as: gaze-on warning, followed by foot-off accelerator pedal, foot-on brake pedal, and gaze-on pedestrian.

Task performance. We also analyzed the test vehicle's deceleration profiles (changes in position, velocity and acceleration over time) during each braking maneuver to extract values for dependent variables such as (1) *stopping distance*, and, (2) *peak deceleration* (Fambro et al., 2007; Fitch et al., 2010; Markkula et al., 2012). The stopping distance was used as a measure of effectiveness of braking and defined as the test vehicle's total travel distance between passing the trigger point and completely stopped. The peak deceleration was derived from the acceleration profile logged during braking and was used as a measure of "braking smoothness" to account for the risk of rear-end collision.

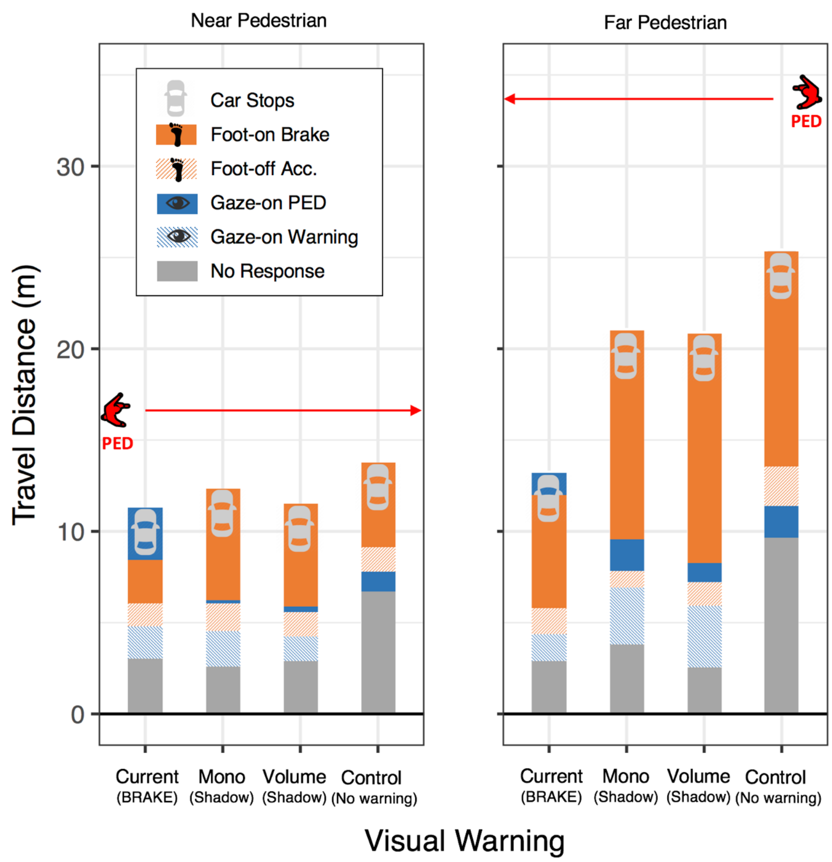

Figure 7.6 The entire process of braking is visualized by distance measures
The test vehicle's mean travel distances in experimental conditions are plotted showing driver behavioral events such as gaze-on warning, gaze-on pedestrian, foot-off accelerator pedal, foot-on brake pedal and finally distance to test vehicle coming to a stop.

7.2.7 Data Analysis

To identify potential main and interaction effects of visual warning and distance to pedestrian on quantitative measures of driver behavior and performance (i.e., travel distances at gaze and foot events, stopping distance and peak deceleration), we performed two-way repeated measures analysis of variances (ANOVA). For the categorical variable, behavioral pattern, we conducted a Durbin's chi-square test, which is a non-parametric equivalent of the repeated measures ANOVA.

7.3 Results

We analyzed data from fourteen participants excluding two drivers who completely ignored the visual warnings and relied on their own driving skill. Eye tracking data from two participants was also excluded from further analysis due to poor quality of data (e.g., scattered or lost gaze data due to reflected ambient light). In the no warning condition, we observed two instances where the driver stopped after passing the pedestrian which were included in the analysis. Figure 7.6 visualizes the entire process of braking with distance-based measures as referenced from the trigger point (*0.0m*) to the pedestrian position (*16.7m* for near condition and *33.5m* for far condition). Results are summarized in Table 7.1 showing descriptive statistics of drivers' mean responses in each experimental condition. Repeated-measures ANOVA tests revealed significant main and interaction effects of visual warning and distance to pedestrian on all 6 quantitative measures (Table 7.2). Therefore, we performed post-hoc contrast tests for planned comparisons among experimental conditions with Tukey's adjustment for multiple comparisons. Only significant differences between experimental conditions are reported herein with details such as mean differences, 95% confidence intervals, and effect sizes, based on guidelines from (Cumming, 2014). For better practical interpretation of the effect size, we report % differences between experimental conditions normalized by mean responses in the control condition that indicate performance gains associated with the visual warnings. Therefore, difference between experimental conditions are reported in the form of ES (d [CI_{lower}, CI_{upper}]), where ES = effect size, d = mean difference between experimental conditions, and [CI_{lower}, CI_{upper}] = lower and upper limits of 95% confidence interval on the mean difference.

7.3.1. Monoscopic versus Volumetric

Participants showed no statistically significant differences in behavior and performance when using monoscopic versus volumetric displays, which were supported by post-hoc contrast tests on all dependent variables between those conditions.

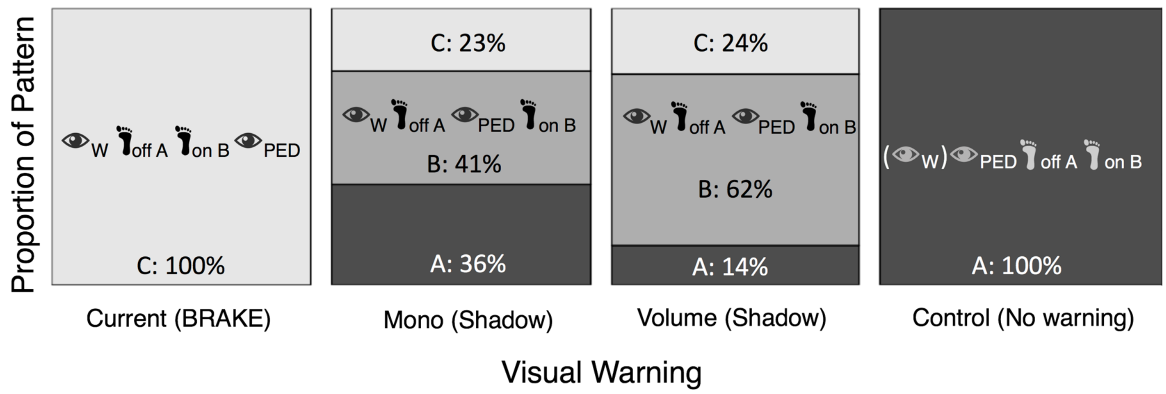

Figure 7.7 Driver behavioral pattern.
When visual warnings were presented via conformal AR graphics (i.e., in both monoscopic and volumetric display conditions), most drivers (77% in monoscopic, 76% in volumetric condition; pattern A + B) looked at the real pedestrian before pressing the brake pedal. In the current warning condition, all drivers reacted to the visual warning and looked for the pedestrian afterward.

7.3.2. Behavioral Changes Caused by Conformal Graphics

Overall, drivers showed a different behavioral pattern when warnings were presented via conformal graphics, as compared to both no warning and current warning conditions (Figure 7.7); A Durbin's $\chi^2(3) = 34.87$, $p\text{-value} < 0.001$. Post-hoc pairwise comparisons revealed differences among all conditions except for between the monoscopic and the volumetric condition. With conformal graphics, most drivers (62% in volumetric; 41% in monoscopic display conditions) exhibited behavioral pattern B such that once they gazed upon the visual warning, they began taking their foot off the accelerator pedal, looked at the real pedestrian, and finally started pressing the brake pedal. If we combine pattern A and pattern B, most drivers (76% in volumetric, 77% in monoscopic display conditions) looked at the pedestrian before they began pressing the brake pedal when the visual warnings were presented via AR conformal graphics. With the current warning, all drivers reacted to the visual warning and looked for the pedestrian after pressing the brake pedal (pattern C).

The distance at which drivers look at the pedestrian (*gaze-on pedestrian*) decreased when warnings were presented via AR conformal graphics in the far pedestrian condition, as compared to no warning condition (Figure 7.8b); in monoscopic display condition by 19.31%

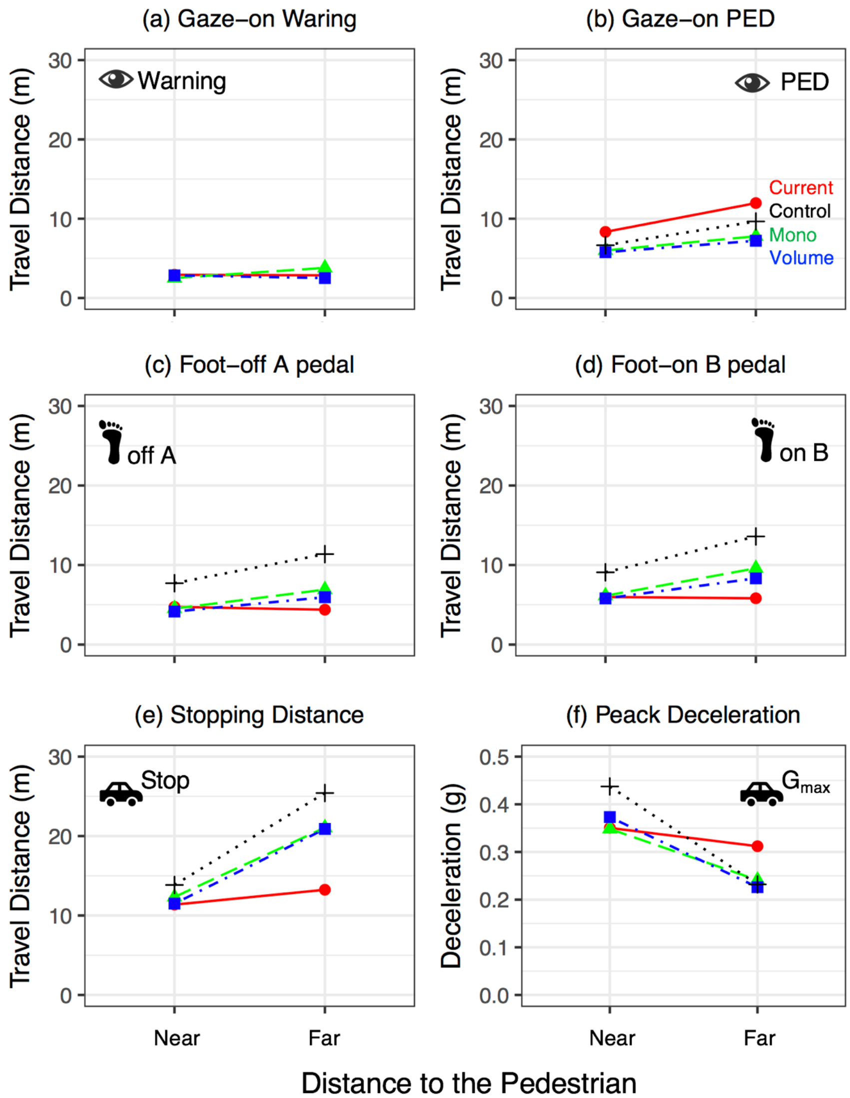

Figure 7.8 Driver braking responses by visual warnings and distances to pedestrian
Gaze-on warning, gaze-on pedestrian, foot-off accelerator pedal, foot-on brake pedal and total stopping distance for the braking task. Peak deceleration was measured in g relative to gravity (*1 g = 9.807 m/s*^{2}). To avoid visual clutter, standard errors of the means were reported in a table (see Appendix A).

(-1.86m [-3.71, -0.02]) and volumetric display condition by 25.21% (-2.43m [-4.28, -0.59]). With the current warning, drivers travelled even farther before looking at the pedestrian, as compared to no warning condition; 24.02% (2.32m [0.48, 4.16]). The same tendency of gaze behavior was observed in the near pedestrian condition as well, but was not found to be statistically significant.

The *foot-on-brake distances* also decreased when drivers viewed AR conformal graphics as compared to no warning condition (Figure 7.8d). In the near pedestrian condition, distances decreased in the monoscopic display condition by 32.44% (-3.02m [-5.42, -0.62]), and the volumetric display condition by 36.15% (-3.48m [-5.84, -1.13]). No differences were found among visual warning conditions. In the far pedestrian condition, the foot-on-brake distances decreased in the monoscopic display condition by 29.42% (-4.50m [-6.82, -2.18]), the volumetric display condition by 38.75% (-5.45m [-7.81, -3.10]), and the current warning condition by 57.21% (-7.82m [-10.14, -5.50]).

7.3.3. Driver Performance Gains from Conformal Graphics

Drivers stopped in shorter distances when visual warnings were given by conformal AR graphics in the far pedestrian situation, as compared to no warning condition at the same distance (Figure 7.8e). The volumetric display condition showed reduction in stopping distance by 17.79% (-4.52m [-6.72, -2.32]), followed by monoscopic display condition by 17.15% (-4.67m [-6.87, -2.47]). The current warning condition (i.e., "BRAKE" sign) showed even more reduction by 49.91% (-12.18m [-14.36, -9.96]). In the near pedestrian condition, warning by conformal AR graphics did not show any reduction in stopping distance, as compared to both no warning and the current warning condition (Figure 7.8e).

All visual warnings reduced peak deceleration of the vehicle in the near pedestrian condition, as compared to no warning condition (Figure 7.8f). The peak deceleration decreased in the monoscopic display condition by 20.34% (-0.10g [-0.15, -0.05]), the volumetric condition by 14.67% (-0.06g [-0.11, -0.02]), and the current warning condition by 19.86% (-0.08g [-0.13, -0.04]). In the far pedestrian condition (Figure 7.8f), warning by conformal AR graphics did not show any reduction in peak deceleration, while the current warning resulted in even higher peak deceleration by 34.46% (0.08g [0.04, 0.12]), as compared to the no warning condition.

7.4. Discussion

The key findings from the empirical study are that (1) the monoscopic head-up display was as effective as the volumetric head-up display for braking performance in AR as measured by stopping distance and peak deceleration, and, (2) visual warnings by conformal AR graphics were associated with qualitatively different driver behavior resulting in improved braking performance. We further discuss possible reasons for the first finding in consideration of available depth cues and their consequences on task performance and depth perception in AR driving. We also discuss implications of the second finding on warning interface design, followed by limitations of this study for generalization of the results.

Regarding driver braking performance, results suggest that perspective depth cues affordable by monoscopic displays are strong enough to ensure human performance in AR driving conditions such as those studies herein. These results contradict our expectation that additional depth cues afforded by a volumetric AR HUD would enable better depth perception and result in better driver performance. In fact, it has been known that volumetric displays outperform monoscopic displays in depth judgments (Bark et al., 2014; Grossman & Balakrishnan, 2006) and localization of hazards in depth is critical for drivers' appropriate reaction and braking performance (Fitch et al., 2010; Langham & Moberly, 2010).

These results further inspire the authors to reconsider characteristics of human depth perception in AR driving. Specifically, there may be more work needed to assess depth perception in AR when drivers are (1) moving fast; (2) in action space; and; (3) immersed in a depth-cue rich real-world augmented by virtual objects which provide additional depth cues atop their real-world referents.

Depth perception from motion is quite different from depth perception while standing still, since the resulting optical flow from motion yields additional depth cues (Nakayama & Loomis, 2016; Simpson, 1993; Swanston & Gogel, 1986). Regarding the driving context, it is even more relevant and important to distinguish z-translation (forward and backward) of the observer's head from xy-translation (side to side or up and down) and its consequences on optical flow, available depth cues and different mechanisms for human depth perception (Peh, Panerai, Droulez, Cornilleau-Pérès, & Cheong, 2002; Wickelgren, McConnell, & Bingham, 2000). Moving one's head side to side generates motion parallax which is known to be a strong depth cue. Whereas, translating one's head in depth at speed (as is the case in driving) generates optical flow away from a expansion point where there is no flow, but from which all flow radiates. The optical flow indicates the heading of a moving observer and provides different kinds of depth cues. After a comprehensive review of literature from physics, computer vision, physiology and experimental psychology, Simpson (1993) showed the relation between optical flow and depth perception, arguing that effective depth cues from motion-in-depth are (1*) changing location*, (2) *changing size* and (3) *changing disparity* over time. The work provides evidence for the integration of dynamic depth cues such that changing location over time (i.e. retinal velocity of images) provides dominant cues for absolute depth judgements which can be reinforced by changing size and disparity. Regan and Beverley compared the effectiveness of monocular and binocular cues from motion-in-depth (i.e. changing size vs changing disparity) and showed that changing-size would be about 76 times more effective than changing-disparity in a pilot's landing task, arguing that precise judgment of motion-in-depth can be made even without binocular vision in some viewing conditions (Regan & Beverley, 1979). In our experiment, it may be possible that the perspective depth cues available in the monoscopic display condition are sufficient for drivers who are moving in depth. To be more specific, changing apparent size and location (i.e., relative size and height in the visual field over time) of the virtual shadow might provide strong depth cues which are sufficiently informative as compared to the incremental information provided in the volumetric display condition at these distances.

Another possible explanation for the results is the *effectiveness of depth cues in action space*. Depth cues additionally provided by the volumetric display (i.e., binocular disparity, motion parallax, convergence and accommodation) are known to be less effective than perspective depth cues in action space (Cutting, 1995). Furthermore, as discussed, perspective depth cues (especially relative height and size) are becoming even more effective and dominant, for the observer who is moving in depth (Simpson, 1993). Therefore, in action space, additional depth cues available in volumetric displays might not be strong enough to make significant differences in drivers' depth perception.

Finally, the *environmental context* might account for no differences between monoscopic and volumetric display conditions observed in this driving context. In fact, there is evidence that shows environmental contexts do effect human egocentric depth judgement. For example, Lappin, Shelton, and Rieser (2006) compared human performance in judging the midpoint to a familiar object in different environments (e.g., an open large field, a hallway, and a lobby) and found that the environmental context affects human depth judgement. The large parking lot in our experiment might affect drivers' depth perception by providing natural depth cues (e.g., linear perspective in a roadway; relative sizes and heights of many parked vehicles). It is also possible that presenting the virtual shadow on the ground plane could affect perceived depth to the shadow, as supported by another empirical study (Kirkley Jr, 2003). Therefore, in the driving context, monoscopic displays might be able to deliver sufficient depth information by leveraging the depth-cue-rich real-world roadway environment.

An integrated analysis of drivers' behavioral patterns and performance revealed the advantage of conformal AR graphics in guiding drivers' attention and its positive consequences in driver perception, localization and reaction to road hazards. The resulting behavioral pattern and reductions in distance measures suggest that the conformal AR

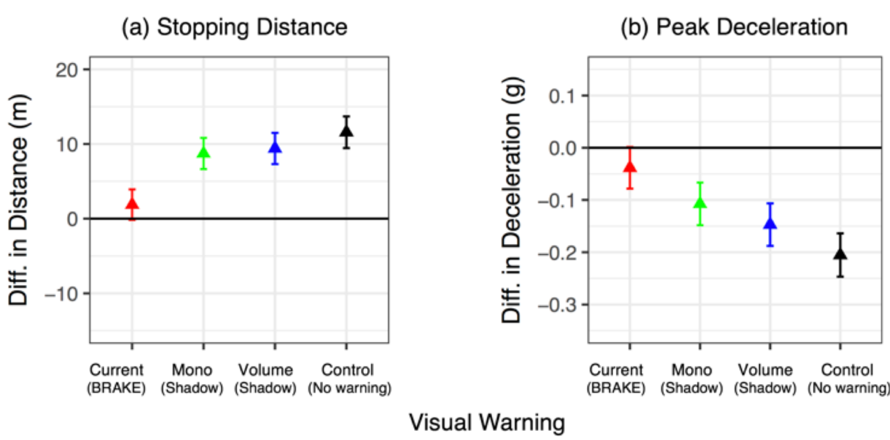

Figure 7.9 Changes in driver braking responses by the distance to the pedestrian
The driver's responses were modulated by the distance to the pedestrian when the warnings were given by conformal AR graphics (in both monoscopic and volumetric display conditions). Mean differences in (a) stopping distance and (b) peak deceleration between near and far pedestrian conditions are plotted with 95% confidence intervals.

graphic warning quickly demanded drivers' attention (gaze-on warning, Figure 7.8a), helped them start reacting to a hazard (foot-off accelerator pedal), guided their attention to the hazard (gaze-on pedestrian) before they executed a confirmative response (foot-on-brake), and resulted in appropriate stopping distances and peak decelerations which were modulated by the distance to the pedestrian (Figure 7.9). This finding is even more obvious when compared to driver's responses in the current warning condition. Since the current warning lacks spatial information about the real-world referent, drivers showed similar responses regardless of the distance to the pedestrian (The 95% CIs intersect with zero in Figure 7.9a and 9b). The current warning's lack of effective attention-guiding cues resulted in unnecessary hard braking even for the far pedestrian (Figure 7.8f) which increases the risk of a rear-end crash. Conversely, the warning interfaces with conformal AR graphics enabled drivers to perceive the threat earlier, brake after locating the pedestrian which resulted in smoother normal braking.

This study furthers our collective understanding about human performance in AR by providing empirical evidence supporting the effectiveness of monocular perspective depth cues in AR driving. The results suggest that monoscopic displays can be as effective as advanced stereoscopic volumetric displays in AR braking tasks by taking advantage of perspective depth cues such as linear perspective, relative size and height in the visual field. A practical implication of this research is that collision warning by conformal AR graphics (via either monoscopic or volumetric displays) can have considerably positive consequences on driver behavior and performance by guiding drivers' attention to relevant real-world objects. By understanding how to design AR driver interfaces that can effectively guide drivers' attention at critical moments (as oppose to divide attention or distract), we can begin to inform design of automotive AR applications.

Despite some limitations, this work is one of the first empirical studies that address human performance with volumetric AR HUDs while driving on real roadways. We also examined a range of human depth perception cues affordable by current AR HUD technologies by using an in-vehicle prototype of volumetric HUD capable of rendering both monoscopic and volumetric views. The proposed approaches and ecologically valid methods presented can be leveraged and further developed by practitioners and future researchers for better understanding about human performance in AR driving and usability evaluation of automotive AR applications. In particular, the analysis of the effects of AR warning interfaces on driver behavioral patterns and braking performance could assist others in determining design and safety tradeoffs.

Finally, this work provides empirical evidence for the relative effectiveness of perspective depth cues in a driving context. Substantial future work is required to fully understand the effectiveness of depth cues for human performance in optical-see through AR; especially when moving through space.

Table 7.1 Descriptive statistics for drivers' braking responses
Drivers mean responses (standard error of the mean, corrected for within-subject variability) in experimental conditions.

Exp. Conditions / Dependent Variables	PED @ near spot				PED @ far spot			
	Control (No warning)	Current (BRAKE)	Mono (Shadow)	Volume (Shadow)	Control (No warning)	Current (BRAKE)	Mono (Shadow)	Volume (Shadow)
travel dist. gaze-on warning (m)	N.A.	2.93 (0.62)	2.49 (0.67)	2.79 (0.67)	N.A.	2.86 (0.62)	3.81 (0.62)	2.51 (0.62)
travel dist. gaze-on pedestrian (m)	6.65 (0.77)	8.34 (0.77)	6.00 (0.83)	5.78 (0.83)	9.65 (0.77)	11.97 (0.77)	7.79 (0.77)	7.22 (0.77)
travel dist. foot-off gas (m)	7.71 (0.77)	4.74 (0.80)	4.53 (0.80)	4.15 (0.77)	11.37 (0.77)	4.38 (0.77)	6.91 (0.74)	5.95 (0.80)
travel dist. foot-on brake (m)	9.09 (0.74)	5.99 (0.76)	6.14 (0.76)	5.80 (0.74)	13.59 (0.74)	5.82 (0.74)	9.59 (0.71)	8.33 (0.76)
total stopping distance (m)	13.84 (0.92)	11.37 (0.87)	12.33 (0.92)	11.50 (0.89)	25.42 (0.90)	13.24 (0.90)	21.06 (0.87)	20.90 (0.90)
peak deceleration (g)	0.44 (0.02)	0.35 (0.02)	0.35 (0.02)	0.37 (0.02)	0.23 (0.02)	0.31 (0.02)	0.24 (0.02)	0.23 (0.02)

Table 7.2 Main and interaction effects of visual warnings and distances to pedestrian on driver responses.
Results of ANOVA tests are reported with F statistics and significance of the effects. **p<.05, **p<.01, ***p<.001*

Dependent Variables	Warning	Distance	W X D
travel dist. gaze-on warning (m)	F(3, 43.61) = 29.47 ***	F(1, 42.73) = 6.22 *	F(3, 42.64) = 3.73 *
travel dist. gaze-on pedestrian (m)	F(3, 32.49) = 9.20 ***	F(1, 42.88) = 30.21 ***	F(3, 42.76) = 1.31
travel dist. foot-off gas (m)	F(3, 31.25) = 13.67 ***	F(1, 42.81) = 18.07 ***	F(3, 42.78) = 3.62 *
travel dist. foot-on brake (m)	F(3, 32.31) = 14.54 ***	F(1, 41.44) = 44.58 ***	F(3, 41.44) = 6.71 ***
total stopping distance (m)	F(3, 35.00) = 28.01 ***	F(1, 11.40) = 159.62 ***	F(3, 31.98) = 19.95 ***
peak deceleration (g)	F(3, 36.29) = 3.92*	F(1, 13.04) = 127.41***	F(3, 38.95) = 12.88 ***

8. Conclusion

8.1 Summary of Key Findings

This dissertation work addressed timely and important human factors research on augmented reality (AR) head-up displays (HUD) in transportation. It aimed to (1) identify information requirements for pedestrian collision warnings, (2) design AR driver interfaces, and (3) quantify the effects of those interfaces on drivers' cognitive processes, behaviors and performance. Considering the dynamic nature of human-environment interaction, we took an ecological approach for interface design and evaluation, appreciating not only the user but also the environment. The requirement analysis examined environmental constraints imposed on the driver's behavior, interface design translated the behavior-shaping constraints into perceptual forms of interface elements, and usability evaluation utilized naturalistic driving scenarios and representative tasks for better ecological validity. This section summarizes key outcomes and findings along the course of AR HUD interface development with possible answers to research questions.

Information Requirements: What are the work demands of automobile driving? What information should be available for the driver to avoid pedestrian collision?

- Environmental demand: The driver's behavior can be shaped by the destination but also bounded by environmental constraints such as stationary (e.g., road geometry), moving (e.g., other road actors) and legal (e.g., traffic signals) obstacles (Figure 3.1). These constraints can be quantified by measurable work domain variables and their relationships (Table 3.1).
- Cognitive demand: To avoid collision, drivers need to detect, localize, identify moving obstacles and evaluate the possibility of collision. The cognitive constraints can be quantified by the required cognitive activities (Figure 3.3 and 3.4), inputs (required information about system states for each activity), outputs (required action on the work domain) and constraints imposed on each cognitive activity in pedestrian hazard situations (Table 3.2).

- Information requirement for pedestrian collision warning: To support the driver's cognitive process, pedestrian's relative position, velocity (heading) and ultimately the predicted minimum spatial gap (headway) should be available to the driver (Figure 3.5).

Interface Design: How can we best present the critical information, identified in the requirement analysis, to the driver?

- The virtual shadow design metaphor was proposed as an augmented reality pedestrian collision warning which can be presented on optical see-through head up displays (Figure 7.4) to leverage the benefit of AR; namely the direct perception of information atop physical reality.
- The virtual shadow visualizes key dynamics of collisions (e.g., changes in predicted spatial intrusion by approaching pedestrians to the vehicle's path over time) via conformal AR graphics integrated in the real-world. The driver's perception of relative movement of pedestrians (which are augmented by the interface) could affect his / her reaction and in turn, the driver's reaction could affect interface dynamics in the close loop interaction (dynamic coupling between perception and action, Figure 5.2).
- The interface design was realized by transforming the driver behavior-shaping constraints into perceptual forms of interface elements such as shape, size and location of AR graphics (Figure 4.1).
- The virtual shadow aims to best support the driver's appropriate behavior by making affordances of the environment (i.e., possibility and consequences of action on pedestrians) salient to the driver.

Analytic Evaluation: Do AR pedestrian collision warnings have the potential to improve the quality of driver information processing?

- By adapting the augmented video and the heuristic walkthrough techniques, we proposed a method for rapid prototyping and usability prediction of AR pedestrian collision warnings by expert evaluators in a driving simulator.
- Quality of driver information processing: A set of heuristics was proposed to help the expert evaluators predict driver workload and performance at each stage of cognitive processing (section 5.2.4). The virtual shadow was expected to improve driver sensation,

attention management, situation awareness and decision-making with reduced workload (Figure 5.4).

- Relationship between interface design factors and driver performance: By adapting a retrospective think aloud technique, we proposed a method for experts to relate expected user performance with contributing design factors for AR graphics, such as the amount of information, shape, size, location, brightness, color and transparency of AR graphics (Table 5.1). Experts predicted positive consequences of specific attributes of the virtual shadow design such as information density, size, position, color and timing of AR cues.
- The comparative usability evaluation showed that the virtual shadow (designed through the ecological approach) has the potential to balance cost and benefit of attentional guidance and thus have positive consequences on the driver information processing, as compared to one of extant technology-driven AR interfaces such as the bounding box.

Empirical Evaluation in a Driving Simulator: What are the effects of AR pedestrian collision warnings on driver situation awareness and workload?

- We proposed operational improvements on the situation awareness global assessment technique to suit AR usability evaluations and better quantify the effects of AR pedestrian collision warnings on driver situation awareness about cued and un-cued environmental elements.
- Situation Awareness: An empirical (n=24) usability evaluation revealed that the virtual shadow improved participants' SA and reduced overconfidence about pedestrians, not affecting their SA about other environmental elements which were not augmented by the AR warning. However, the bounding box showed negative side effects on driver SA such that it degraded driver situation awareness about un-cued environmental elements, suggesting that poorly designed AR interfaces could cause cognitive distraction by degrading users' situation awareness about other critical environmental elements which are not augmented by AR interfaces.
- Workload: No evidence was found for reduced driver workload when AR warnings were given. Future work could include not only subjective but also objective measures for workload to better understand the effects of AR warnings on driver workload.

Empirical Evaluation in a Parking Lot: What are the effects of AR pedestrian collision warnings on driver behavior and performance?

- We proposed a method for on-road usability evaluation of AR pedestrian collision warnings including a working prototype of AR driver interfaces on an in-vehicle volumetric head-up display, experimental setups, procedures and task scenarios aiming for better ecological validity (see section 7.2 for details).
- Behavior and performance: An empirical (n=16) evaluation suggests that visual warnings by conformal AR graphics were associated with qualitatively different driver behavior resulting in improved braking performance. The virtual shadow enabled drivers to perceive pedestrian threats earlier, brake after localizing pedestrians which induced smoother normal braking and reduced total stopping distances with lower peak decelerations.
- Efficacy of monocular depth cues: This study also provides empirical evidence suggesting that conformal graphics presented via monoscopic HUDs can be as effective as advanced stereoscopic displays in AR braking tasks by leveraging the effectiveness of monocular perspective depth cues such as linear perspective, relative size, and height in the driver's visual field.

In sum, this work suggests that AR pedestrian collision warnings, which convey spatial information via conformal graphics, have potential benefits over existing pedestrian collision warning interfaces in driver attention management, situation awareness, performance with reduced workload.

8.2 Contributions

This research has shown that there exists significant opportunity to further incorporate the ecological approach into AR application interface design and evaluation. It contributes both basic and practical research topics on human factors in AR by (1) furthering our collective knowledge about human performance in AR and (2) extending traditional methods for AR interface design and evaluation. Specifically, this work provides:

- *Empirical evidence* for benefits of conformal AR graphics in driver situation awareness, behavior and performance by guiding drivers' attention to relevant real-world objects.
- *Empirical evidence* for the efficacy of monocular perspective depth cues for human performance in AR braking tasks.
- A novel AR *driver interface* for pedestrian collision warning, the virtual shadow.
- A rapid prototyping and usability evaluation method for automotive AR applications by extending augmented video and heuristic walkthrough techniques adapted in a driving simulator.
- A set of *heuristics* for AR usability evaluation which predicts the driver's workload and performance in sensation, attention management, situation awareness and decision making while interacting with AR.
- A *usability evaluation method* for identifying AR design factors which contribute to user performance by extending the retrospective think aloud technique.
- A *usability evaluation method* that quantifies effects of automotive AR applications on driver situation awareness about environmental elements both cued and un-cued by AR graphics, by adapting the perceptual matching and situation awareness global assessment techniques for AR usability evaluation.
- An ecologically valid *usability evaluation method* for AR pedestrian collision warnings on real roadways including experimental setups, procedures and task scenarios.
- An *analysis method* for driver gaze, foot behavior, behavioral patterns, and braking performance while interacting with AR pedestrian collision warnings.

The proposed pedestrian warning, the virtual shadow, can benefit *vehicle drivers* by reducing attentional demand, improving situation awareness and finally resulting in reduced pedestrian accidents. This research also benefits AR *researchers* by providing insight on the effects of AR HUD user interface designs on drivers' cognitive processes, behavior and performance. Furthermore, the proposed approaches and methods can be leveraged and further developed by *designers and practitioners* to inform the interface design and usability evaluation for safer and more effective automotive AR applications.

8.3 Limitations and Open Research Questions

The proposed sets of prototyping methods, experimental design, environment, task scenario, and performance measures have the advantage of better ecological validity but also have limitations for generalization of our findings to other situations.

The usability evaluations in a driving simulator presented driving footage captured in natural real-road setting for better ecological validity. However, driving tasks for the participants in those studies - mimicking driving - may not have fully imposed actual demands (visual, cognitive and manual) of driving, despite our best efforts via operational manipulations. Future work is required to understand the representativeness of this method in terms of task demand and difficulty. Nevertheless, this method is still useful as a rapid prototyping and evaluation technique which complements downstream empirical usability evaluations along the entire process of interface development.

The proposed operational improvement on the situation awareness global assessment technique could be problematic in field studies, since it still requires freezes in the task scenario. This problem is inherent in the situation awareness global assessment technique and might be attenuated to some extent by additional operational improvements. Further improvements or development of new method are required for field studies.

The effectiveness of monocular depth cues on driver performance in AR was supported by our experimental results. However, the possible reasons for this finding (i.e., effectiveness of depth cues on driver depth perception in AR) were not directly supported by this experiment, even though we provided some promising evidence from the literature about modulating factors such as motion-in-depth, action space and environmental context. Systematic investigations of these factors are required to better understand human depth perception in a moving, dynamic AR driving context.

Another limitation of the empirical study in a parking lot is the use of different visual stimuli across experimental conditions, especially for the current warning interface condition. The comparison between monoscopic and volumetric conditions does not have any concern. However, the use of “BRAKE” sign might limit the validity of our comparison with visual warnings presented via conformal AR graphics, even though such comparison has a practical meaning to answer a simple question; How much better is an AR-based warning interface than the current one? Lastly, we note that the "BRAKE" sign might further affect drivers' responses, as Lorenz, Kerschbaum, and Schumann (2014) showed the different consequences of command display versus status display in driving contexts.

The depth-cue rich parking lot was an ecologically valid setting but the results from this environment may not apply to other situations such as nighttime driving which is a more challenging environment in terms of pedestrian collision avoidance. Moreover, depth-based information available in daytime driving would be attenuated greatly at night including the actual pedestrians, the real-world referents of the virtual shadow, and other critical depth cues such as linear perspective, ground plane and optical flow. Future studies should address the scalability of these findings by performing similar tests in various environmental and lighting contexts.

Additionally, the task scenario in the parking lot study included only parts of task demands of driving and the results from this study might not be applied to other types of driving tasks. Specifically, the collision avoidance task requires significant bottom-up, stimulus driven information processing whereby unexpected road events initiate drivers' information processing for appropriate reaction (Endsley, 2012). Other types of driving task, such as navigation, may require a top-down, goal-driven information processing whereby a specific goal in mind will direct drivers' information processing. Future work is required to examine the effects of AR HUD depth cues on different types of driving tasks.

Finally, participants' expectancy of road events should be further addressed in future work. In the parking lot study, we added one no-event trial and backing-up vehicle event per participant to reduce drivers' expectancy of pedestrians. Counterbalancing the presentation order helped evenly distribute learning and ordering effects across experimental conditions, but expectancy could still be an issue to further explore. Future work could introduce more no-event trials or various other events to address this problem. Lastly, to address drivers' adaptation or acceptance of new AR HUD technology, a longitudinal observational study could be conducted to examine changes in drivers' confidence, behavior, and performance while using AR pedestrian collision warning systems over time in various situations.

8.4 Future Research Direction

Given advances in display, sensor and communication technology such as the internet of things, AR is expected to become more popular, affordable and ubiquitous in the near future. However, in order to realize the full potential of this novel technology, AR must be more usable and useful than it is currently, and in this area, human factors research can have unique and significant contributions. Therefore, substantial future work is required for both ***basic*** and ***applied research*** on ***human factors in AR***.

Basic research can aim to ***make AR more usable*** by addressing challenges in human perception, attention and cognition while interacting with AR. This dissertation work inspired various research topics such as:

Depth misperception caused by AR graphics can limit the efficiency of interaction in personal space (e.g., dexterous manipulation of physical objects augmented by digital overlays) or action space (e.g., localization of approaching objects while driving for appropriate reaction). Systematic investigations are required to better understand the dynamics of human depth perception when interacting with AR. Established knowledge about the effectiveness of different depth perception cues (e.g., binocular disparity, motion parallax, relative size and heights) from stationary observers should be extended to those of moving observers (such as vehicle drivers) to support interaction with AR "on the go".

Focal depth mismatch between AR graphics and their real-world referents can cause perceptual problems (e.g., defocus blur and dual images) and demand users to excessively switch focus between digital and physical objects. Future work is required to systematically investigate just noticeable differences in human depth of field where both digital and physical objects at different depths are in focus without the need for shifting focus. Research findings will inform display and interface design for better usability.

Real-world backgrounds can change perceived color of AR graphics when seen through transparent displays, which can challenge interface designers to convey meanings with colors (e.g., red is for danger or stop, orange for warning, green for go). Further work is required to identify characteristics of colors that make them robust so that they retain their intended color semantics despite changing backgrounds. Thresholds of human performance (e.g., ability to name the color correctly) can be tested against varying levels of backgrounds and AR graphics.

AR graphics can be distractive by narrowing users' attention, as observed in our driving simulator study. This is challenging because users must interact with not only information on the AR display but also with changes in the environment. For the widespread adoption of AR applications, future work is required that investigates methods to quantify and manage the distraction potential of AR applications. For example, visual distraction can be quantified by measurement of how well users can detect un-cued information while interacting with information cued by AR graphics. Cognitive distraction can be quantified by comparison of users' situation awareness with and without using AR applications, as this work demonstrated in the driving context.

Applied research efforts can aim to ***make AR more useful*** by (1) identifying promising use cases that can benefit from AR, and (2) designing AR interfaces that make *affordances* of the environment (i.e., possibilities and consequences of action on objects) salient to the user so as to best support the user's goal-directed behavior.

Among many potential applications, driving is one of the more promising tasks, where conformal AR graphics integrated in the real-world can guide users' attention to task related environmental elements to enhance driver performance and safety. AR heads-up displays can be effective and intuitive driver-vehicle interfaces for advanced driver assistant systems (e.g., navigation aid and various crash warning systems) and connected vehicle communications such as those needed for emerging vehicle-to-vehicle, vehicle-to-infrastructure and vehicle-to-devices environment. Future work should identify compelling use cases to leverage currently available ADAS and V2x communication. The best presentation methods can then be investigated to support each use-case by examining user interface design factors such as design metaphors, contrast in color and brightness, layout, density, and placement of information (in both field of view and depth of field).

Finally, while engineers are advancing technologies for AR applications, human factors researchers must keep their eyes on the most important things behind the AR glasses; the human.

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Appendices

Appendix A. Summary: Human Factors Research on AR HUDs

Group1: Supporting primary tasks with world-fixed cues for wihthin FoV objects

Pur.	Info.	Display Type		Experiment				Task		Findings
		HW	FoV	Exp. Design	DV	Sub.	Scenario	Driving	Non-Driving	
FCW	Lane availablility	HUD (sim)	Full	BTW 3 cue type (no, command, status)	RT, Reaction Type (steering, brakinng, S+B)	n = 46, g =3, age 20-54	incident (crased cars in front)	responding to unexpected event	Interacting w/ center console display	command display are better than status display in urgent situation (Lorenz 14')
Night Vision	Highllighted road edges	HUD (sim)	Full	WITHIN 3X2 cue type, visibility	Gaze pattern, headway, lane dev, RT, collision	n = 30 age 22-31	incident (sudden obstacles)	responding to unexpected event while nighttime driiving	no	visibility enhancement of lane marker *reduced* safety (Sharfi 14')
Left turn aid	Projected path of oncoming veh.	HUD (**act**)	C,20° (circle)	WITH 2X2 cue type, speed of oncoming vehi.	Gap acceptance	n = 4	high traffic volume	left turn	no	conservative driving w/ AR cue (Tran 13')
FCW	TTC to lead veh.	HUD (sim)	Full	Mixed 2X2X2 BTW age WITH AR cue presence, secondary task presence	RT, collision, TTC	n = 24 g = 2 age 18-30, 60-75	incident (slowing, merging traffic / 3 min)	car following	distraction task: hands-free phone conversation	AR cue reduced forward collion. differential effect of age group; younger drivers reduced headway Wai-Tat 13')
FCW	Location of obstacles	HUD (sim)	Full	WITH 2X2 AR cue presence, Cue reliiability	Detection accuracy of uncued obj, RT, TTC	n = 20 age 65-85	12 road side objj	identifying hazard, car following	push button when detect roadside obj	AR cues improved hazard detection w/o interferencing headway control (Shall 13')
FWC	Time headway	HUD (sim)	Full	BTW 2 AR cue presence	headway, acceleration, jerk	n = 22 age 19-36	mid traffic volume	car following	no	Reduced THW within safe range (>1 sec), (Saffarian 13')
Navi	Virtual cable in the air	HUD (sim) HDD	Full	WiTH 3 Type of Navi (AR HUD, Street View HDD, Map View HDD)	Dwell time, workload, driving performance (lane, dev speed...)	n = 18 age 18-37	incident (jaywalking pedestrian,unexpected brakings)	responding to unexpected event, navigation	no	AR HUD showed lease negative impact on driving and workload (Medenica 11')
Visibility Enhancement	Bounding box of near cars, Color coded lanes...	HUD (sim) HDD	Full	WITH Type of Navi (HUD, HDD)	# of collision, heaway, speed, subjective rating	n = 40	incident (sudden braking and trffic congestion)	responding to unexpected event, car following	no	AR HUD reduced collision in foggy driving (Charissis 10')
Navi	Unrolling map	HUD (sim) HDD	Full	Mixed 2X2 BTW age WITH Type of Navi (HUD, HDD)	Error (missed turns, rule violation), Gaze pattern	n = 24 g =2 age 19-41 ,66-85	incident (jaywalking pedestrian)	responding to unexpected event, navigation	no	diffrential eff of age groups. no performance difference in younger group even more time on the road w/ HUD (Kim 09')

Group2: Supporting primary tasks with screen-fixed cues for outof FoV objects

Pur.	Info.	Display Type		Experiment				Task		Findings
		HW	FoV	Exp. Design	DV	Sub.	Scenario	Driving	Non-Driving	
Speed CTR	Current speed and speed limit	**HUD (act)**	Full	WITH AR cue type (no, road sign, number, symbol)	RT, head pose	n = 11 age 22-50	real road driiving	speed control (responding to speed limit)	no	AR cue reduced RT, Head pose tracking is more reliable than eye tracking on raod (Doshi 09')
Interse ction approaching	Virtual traffic light	HUD (sim)	D 4°X5°	Mixed 2X 3X2X2 BTW age, WITHIN cue type, signal change, timing of change	Gaze pattern, Behavior on yellow sign, Pedal response	n = 24 age 18-24 ,65-76	mid traffic volume	speed control (responding to traffic light)	no	AR cues cused more frq stopping and reduced speed @ intersection, Younger drivers had longer and freq fixation on HUD (Caird 08')
Blind Spot Alert	Wind vane indication direction of danger	HUD (pro to)	Full	WITH 2X2 Frame of reference, Auditory cue	RT to alert, driving measures, workload	n = 24	incident (imminent dangers)	lane keeping	verbal response to imminent danger	Egocentric AR cues outperformed exocentric ones (Tonnis 06')

Group3: Supporting primary tasks with screen-fixed cues for within FoV objects

Pur.	Info.	Display Type		Experiment				Task		Findings
		HW	FoV	Exp. Design	DV	Sub.	Scenario	Driving	Non-Driving	
FCW Speed CTR	Hazardous lead veh., Speedometer	HUD (act) HMD (act)	D 14° C 23°	WITH Display type	Pedal response (RT, error), PDT (RT, error)	n = 34, age 23-57	incident (braking of lead veh, change of speed lim.)	responding to unexpected events	Peripheral detacton	No diff. in PDT and response to unexpected events with HUD and HMD (Lauber 13')
FCW Speed CTR	Hazardous lead veh., Speedometer, etc	HUD (sim)	D 4°X5°	WITH # of symbols	Driving (lane dev), Readout (RT, error), PDT(RT, error)	n = 18	mid traffic volume	car following, read out speedometer	Peripheral detacton	Driving, readout and PDT performance impaied by complexity of symbols. (Burnett 12')
Curve Alert	Curvaute of road	HUD (sim)	D 4°X5°	WITH 4X3X2 Auditory, Visual (no, HDD, HUD), Haptic	Pedal response (RT)	n = 24 age 18-25, >60	incident (sudden braking lead veh)	speed control (responding to speed limit) and lane keeping		AD outperformed HUD and HDD. Similar performance btw HUD and HDD (Neurauter 05')
FCW Speed CTR Navi.	Alert Symbol, speedometer, driving instruction	HUD (sim)	D 6.5°X 4°	MIXED 3X3 Type of display (HUD, HDD, auditory), age	Response to in-vehicle and ext. stimuli (RT, error)	n = 36 age 25-55, 26-74, >75	incident (sudden braking lead veh)	observing videotaped driving scene	Responding to events by pushing buttons	AD outperformed HUD and HDD. Similar performance btw HUD and HDD (Gish 99')

Group4: Supporting secondary tasks

Pur.	Info.	Display Type		Experiment				Task		Findings
		HW	FoV	Exp. Design	DV	Sub.	Scenario	Driving	Non-Driving	
Menu selection	Hierachy of menu items	HUD (sim)	R	WITH 3X3 modality (A, V, A+V), secondary tasks difficulty	lane dev, speed, rule violation, # of crash	n = 30 age 21-56	repetition of high and mid traffic volume	Land keeping	change destination, change fan speed, temperature, tune radio, read email	All displays reduced driving performance (Jakus 15')
Texting	Incoming text message	HMD (Glass) HDD (Smart Phone)	UR 11.5° X7.5°	WITH Display (no, HMD, HDD)	RT, workload, driving performance	n = 40	incident (unexpected braking lead veh)	car following	texting (message requires arithmetic task e.g. 1634-17)	Cost of wearing glass. Texting impaired driving regardless of device. Glass did not lead to better RT to unexpected event (Sawyer 14')
Commu.	Volume of music Caller Name, Recommended new route	HUD (proto) HMD (act)	C 14° C 40°	MIXED 2X3 WITH disp type, BTW input method (rotary dial, gesture)	Driving performance, Secondary taks performance, workload	n = 37	low traffic volume	route change due to traffic condition, car following	audio control, incoming text (navigation info), incoming call	Horizontal gesture of one hand caused unintentional steering with other hand. No diff. in driving performance. No control group (Lauber 14')

Appendix B. IRB Approval

VirginiaTech

Office of Research Compliance
Institutional Review Board
North End Center, Suite 4120, Virginia Tech
300 Turner Street NW
Blacksburg, Virginia 24061
540/231-4606 Fax 540/231-0959
email irb@vt.edu
website http://www.irb.vt.edu

MEMORANDUM

DATE:	March 17, 2016
TO:	Joseph L Gabbard Jr, Hyungil Kim, Matt Davis, Martha Irene Smith, Jessica Danielle Isleib
FROM:	Virginia Tech Institutional Review Board (FWA00000572, expires January 29, 2021)
PROTOCOL TITLE:	Augmented Reality Heads-Up Display for Pedestrian Safety
IRB NUMBER:	**15-300**

Effective March 17, 2016, the Virginia Tech Institution Review Board (IRB) Chair, David M Moore, approved the Continuing Review request for the above-mentioned research protocol.

This approval provides permission to begin the human subject activities outlined in the IRB-approved protocol and supporting documents.

Plans to deviate from the approved protocol and/or supporting documents must be submitted to the IRB as an amendment request and approved by the IRB prior to the implementation of any changes, regardless of how minor, except where necessary to eliminate apparent immediate hazards to the subjects. Report within 5 business days to the IRB any injuries or other unanticipated or adverse events involving risks or harms to human research subjects or others.

All investigators (listed above) are required to comply with the researcher requirements outlined at:

http://www.irb.vt.edu/pages/responsibilities.htm

(Please review responsibilities before the commencement of your research.)

PROTOCOL INFORMATION:

Approved As:	**Expedited, under 45 CFR 46.110 category(ies) 6,7**
Protocol Approval Date:	**April 7, 2016**
Protocol Expiration Date:	**April 6, 2017**
Continuing Review Due Date*:	**March 23, 2017**

*Date a Continuing Review application is due to the IRB office if human subject activities covered under this protocol, including data analysis, are to continue beyond the Protocol Expiration Date.

FEDERALLY FUNDED RESEARCH REQUIREMENTS:

Per federal regulations, 45 CFR 46.103(f), the IRB is required to compare all federally funded grant proposals/work statements to the IRB protocol(s) which cover the human research activities included in the proposal / work statement before funds are released. Note that this requirement does not apply to Exempt and Interim IRB protocols, or grants for which VT is not the primary awardee.

The table on the following page indicates whether grant proposals are related to this IRB protocol, and which of the listed proposals, if any, have been compared to this IRB protocol, if required.

Invent the Future

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
An equal opportunity, affirmative action institution

Appendix C. Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants in Research Projects Involving Human Subjects

Title of Project: Driving with Augmented Reality Displays for Pedestrian Safety

Investigators: Hyungil Kim and Joseph L. Gabbard

I. Purpose of this Research/Project

To improve driver performance on pedestrian detection and collision avoidance, novel augmented reality (AR) driver vehicle interfaces are proposed. This explorative study is aiming to evaluate usability of different design metaphors for the driver vehicle interface of pedestrian detection systems to facilitate better design with possible future iterations.

II. Procedures

A. Participant Selection

To be considered for this study, you must be an adult, over the age of 18, with no visual concerns (after corrected using glasses) that may prevent you from performing driving during daily life.

B. Time Requirements

You will be asked to come to COGENT Laboratory, Whittemore Hall, Room 530B, Virginia Tech. The entire study may take up to one hour.

C. Study Procedures

On the experiment day, you will go through the consent process first. The research staff will describe to you what you will be doing in the experiment; show you the equipment they will be using, and show the interface they will be using. If you decide not to participate in the study, you will be thanked and free to leave. The entire study will take about an hour.

If you decide to participate in the study, you will be asked to sit on a driving simulator equipped with a stationary real car cab. You will be given 10 minutes to familiarize yourself with the driving simulator and tasks.

You will then be asked to perform driving tasks that require you to manipulate the steering wheel and pedals to get to the given destinations, route plans or navigation instructions.

Near traffic will be introduced and you should appropriately respond to any event as you usually drive a car. During your driving, you will be asked to wear eye tracking glasses and your eye gaze will be recorded. The driving scenarios will be paused several times randomly and you will be asked to questions about situation when the scenarios are paused. You will perform these tasks both with and without augmented reality visual aids. After each driving trial, you will be asked to estimate your workload by giving 1-10 rating scales.

At the end, you will be thanked and asked to fill out a questionnaire to give opinions on your driving experience. The all driving trials will be video-taped for further analysis of your responses.

III. Risks Involved in Participation

There are no more risks than everyday activities and playing a console driving game.

IV. Benefits from Participation

You are not promised any specific/direct benefits for your participation in this study. The results of this study may yield benefits to the drivers through the design and development of a novel driving interface.

V. Extent of Anonymity and Confidentiality

You will be signed a unique individual code number. The code number will be used on all of your study documents and data files. The Principal Investigator (PI), Dr. Gabbard, will maintain a code key list to link your personal information to the code number used on your data. The code key list will be kept locked in a filing cabinet in the PI's office and will not be accessible to anyone who is not a project staff member. Coded data will be stored on a computer with password-protected access, and hard copies of data will be kept in a locked filing cabinet in the lab or in the PI's office. At the conclusion of the study, the data will be analyzed and will be published in scientific journals. You will not be identified in the publications, and your anonymity and confidentiality will be maintained. As required by federal law and Virginia Tech IRB Policy, study records will be maintained for 7 years after the conclusion of the study, after which time they will be destroyed.

VI. Compensation

No monetary compensation will be provided for participants in this study.

VII. Freedom to Withdraw

You are free to withdraw from the study at any time and for any reason. Should the researchers determine that you should be removed from the study, you will be thanked and excused.

VIII. Subject Responsibilities

You are expected to provide accurate information on the questionnaire. You are expected to adhere to your scheduled participation dates, advising the PI if the date(s) need to be rescheduled, unless you decide to withdraw from the study.

IX. IRB Review of Research

The Virginia Tech Institutional Review Board (IRB) for projects involving human subjects, has reviewed this proposed study, and has determined that it is in compliance with federal laws and Virginia Tech policies governing the protection of human subjects in research. However, you should recognize that the review does not constitute an endorsement of the research, and that it is up to you to determine whether you are willing to participate in the study after having been informed of the risks, benefits, and procedures involved in this study.

X. Subject / Participant's Permission

I have read the Consent Form and conditions of this project and have discussed it with the research staff or PI. I have had all my questions answered to my satisfaction. I hereby acknowledge the above and give my voluntary consent to participate in this study:

____ Date__________
Subject's Signature

Subject's Project Identification Code: _____________

Should you have any questions about this research or its conduct, research subjects' rights, and whom to contact in the event of a research-related injury to the subject, you may contact:

Joseph. L. Gabbard	Principal Investigator 540-231-3559 (office) jgabbard@vt.edu (email) Department of Industrial and Systems Engineering, Virginia Tech Blacksburg, VA 24061
David M. Moore	540-231-4991 (office) moored@vt.edu (e-mail) Chair, Virginia Tech Institutional Review Board for the Protection of Human Subjects Office of Research Compliance

Appendix D. Pre-test Survey

0 Introduction

Hello, welcome to the study. We are studying driver experience and performance with a novel technology of augmented reality head-up displays. A head-up display is a transparent display that presents information on the windshield so that you don't need to look down to get information.

During the experiment, you will be asked to drive a mini cooper in our driving simulator interacting with new driver vehicle interfaces. While you are driving, your eye gaze will be recorded. After your driving, you will be asked to answer questions and rate your experience.

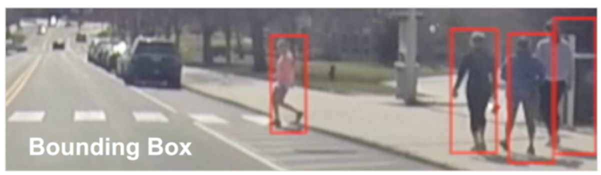
First of all, would you show me your driving license? (if not, reschedule the study)

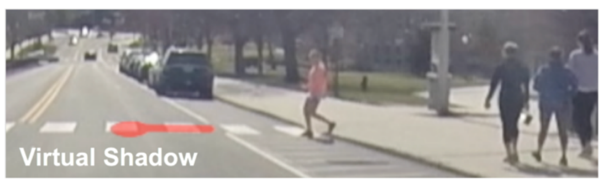
Please read this informed consent form carefully and sign at the back.
(Hand over the form)
Thanks for participating the study again.

We designed some driver vehicle interfaces that aim to help you detect pedestrians and avoid collisions. Here is an example of interface designs you may see.

(Show the picture of examples of interface designs)

Examples of driver interfaces on the windshield for pedestrian collision warning





You may or may not see either "bounding boxes" or "Virtual Shadows" for pedestrians around you.
* The bounding boxes will show up whenever the car detect pedestrians and highlight them with boxes.
* The virtual shadow will show up only when the car expect collisions and show the predicted location of collision by approaching pedestrians.

We're going to evaluate usability of these interface designs and use the result from this study to design a better driver interface.

This study will take about 1 hour. It will start from a short survey on your basic demographic information and driving experience. Then, you will be asked to drive a mini cooper in our driving simulator. You will have 1 practice driving trial and 3 test driving trials. I will describe these in more detail once you are in the driving simulator. At any point, If you wish to stop the study for any reason, please let me know immediately and I will stop the study. Your personal information will be kept separate from the data collected during your runs. Please provide accurate information on all questionnaires.

(Retrieve the pre-test survey form and assign participant ID)

SUBMIT

1 Demographics

Assign a participant ID first

* Required

Participant ID *

P1

How often do you experience motion sickness, particularly when being in a car or moving vehicle? *

If "always" or "frequently", please speak to the experimenter.

- ◯ Always
- ◯ Frequently
- ◯ Sometimes
- ◯ Rarely
- ◯ Never

Gender *

- ◯ Male
- ◯ Female
- ◯ Other: ____________

Age *

Your answer

At what age did you receive your driver's license? *

Your answer

How many years have you been actively driving? *

Your answer

What types of vehicles do you usually drive in your household? *

- ☐ Passenger car
- ☐ Sport-Utility Vehicle
- ☐ Pickup Truck
- ☐ Mini-van
- ☐ Crossover
- ☐ Motorcycle
- ☐ Hatchback

Over the past two years, what is your average annual driving mileage (estimate)? *

- ○ Less than 5,000 miles
- ○ 5,000 - 10,000 miles
- ○ 10,000 - 15,000 miles
- ○ 15,000 - 20,000 miles
- ○ 20,000 - 25,000 miles
- ○ 25,000 - 30,000 miles
- ○ More than 30,000 miles

Approximately how many hours did you drive per week last year? *

Your answer

Describe the kind(s) of driver training that you received prior to getting a license and throughout your driving experience. *

- ☐ Informal driver training offered by a parent, family member or friend
- ☐ Driver's Education offered through school
- ☐ Driver's Education offered through private company
- ☐ Operated farm equipment or lawn tractors
- ☐ Motor sports experience
- ☐ Post-licensure driver skills training/enhancement
- ☐ Other:

How would you rate your driving ability compared to the average driver? *

- ○ Much better
- ○ Somewhat better
- ○ About the same
- ○ Somewhat worse
- ○ Much worse

How do you restrict your driving? *

- ☐ Avoid driving at night
- ☐ Avoid highway or interstate travel
- ☐ Avoid left turns across traffic, where possible
- ☐ Avoid high traffic volumes
- ☐ Avoid driving in unfamiliar areas
- ☐ Not at all
- ☐ Other:

In the past 2 years, how many crashes that were, or could have been, police-reported have you been in? *

- ○ 0
- ○ 1
- ○ 2 or more

Crash: Were you at fault?

- ○ Yes
- ○ No

Do you have any experience using augmented reality applications? *

- ○ Yes
- ○ No

If you have used augmented reality applications before, please explain how or when you used it.

Your answer

SUBMIT

Page 1 of 1

Never submit passwords through Google Forms.

Appendix E. Presentation Order of Experimental Conditions

Driving **S**cenario = {S1, S2, S3}, Warning Interface **D**esign = {D1, D2, D3}

Participant	Trial 1	Trial 2	Trial 3
P1	S2D1	S3D3	S1D2
P2	S1D3	S2D2	S3D1
P3	S3D2	S1D1	S2D3
P4	S1D2	S2D1	S3D3
P5	S3D3	S1D2	S2D1
P6	S2D1	S3D3	S1D2
P7	S1D3	S3D2	S2D1
P8	S2D2	S1D1	S3D3
P9	S3D1	S2D3	S1D2
P10	S3D1	S1D2	S2D3
P11	S2D3	S3D1	S1D2
P12	S1D2	S2D3	S3D1
P13	S2D3	S1D2	S3D1
P14	S1D1	S3D3	S2D2
P15	S3D2	S2D1	S1D3
P16	S3D2	S1D3	S2D1
P17	S1D1	S2D2	S3D3
P18	S2D3	S3D1	S1D2
P19	S1D2	S3D1	S2D3
P20	S3D1	S2D3	S1D2
P21	S2D3	S1D2	S3D1
P22	S3D1	S1D2	S2D3
P23	S2D2	S3D3	S1D1
P24	S1D3	S2D1	S3D2

Appendix F. Results of Goal Directed Task Analysis

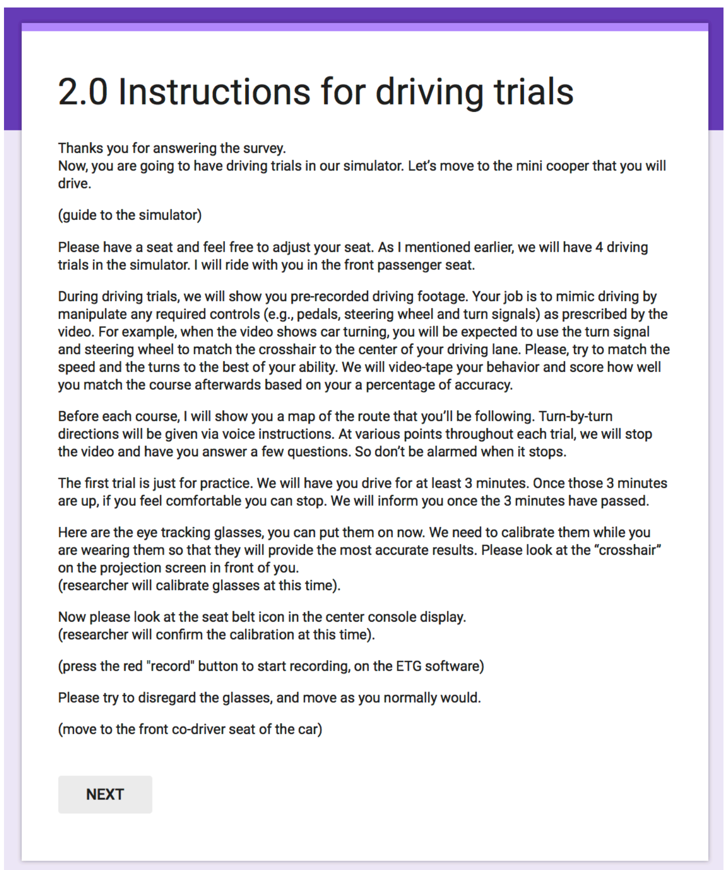
Drivers Goal Hierarchy (Decomposition of goals)		**Decision** to be made to achieve the goals	**Required Information** to make decision
Strategic	Route planning	• Where am I? detection of landmarks understanding meaning of landmarks • Where are next navigational choice points? prediction of upcoming landmarks	**Geographical area** SA1: landmarks SA2: current position SA3: navigational instruction
Tactical	Maneuvers *(Execute route plan)*	• Does my car maintain good status? detection of gage values (e.g. fuel gage) understanding meaning of values (e.g. normal?) • Will my car maintain good status? prediction of future status (e.g. fuel range)	**My car status** SA1: Gage value SA2: Normality of value SA3: Predicted value
		• What are allowed actions? detection of traffic lights, road signage understanding of valid signs/signals prediction of signal change (e.g. intersection approach)	**Traffic signals/road signs** SA1: Type of signs/signals SA2: current status SA3: future status
	Event responding **• Preventing collision (e.g. pedestrians)**	• Who are in my path? **detection of PEDs** • Who are going to cut in my path? **understanding PEDs' intention** • Possibility of collision? **prediction of PEDs' movements**	**Other road actors** SA1: current position SA2: heading SA3: projected path **PEDs' current position** **PEDs' heading** **PEDs' projected path**
Operational	Lateral control	• Am I drifting?	Lane position
	Longitudinal control	• Am I speeding • Am I tailgating?	Speed and speed limit Headway

Appendix G. Examples of SA Queries

Instructions for Experimenters

- Questions will vary depending upon situation when the simulation pauses. Whenever the simulation pauses, please ask 3 questions about the situation. Do not hand over the form to the participants. Dictate participants' response on a given form on the iPad.
- Maps or pictures will be shown on the driving simulator screen for some questions, if required.
- Right after participants, answering each question, ask subjective rating on their confidence level on each answer.

Instructions for Participants



2.0 Instructions for driving trials

Thanks you for answering the survey.
Now, you are going to have driving trials in our simulator. Let's move to the mini cooper that you will drive.

(guide to the simulator)

Please have a seat and feel free to adjust your seat. As I mentioned earlier, we will have 4 driving trials in the simulator. I will ride with you in the front passenger seat.

During driving trials, we will show you pre-recorded driving footage. Your job is to mimic driving by manipulate any required controls (e.g., pedals, steering wheel and turn signals) as prescribed by the video. For example, when the video shows car turning, you will be expected to use the turn signal and steering wheel to match the crosshair to the center of your driving lane. Please, try to match the speed and the turns to the best of your ability. We will video-tape your behavior and score how well you match the course afterwards based on your a percentage of accuracy.

Before each course, I will show you a map of the route that you'll be following. Turn-by-turn directions will be given via voice instructions. At various points throughout each trial, we will stop the video and have you answer a few questions. So don't be alarmed when it stops.

The first trial is just for practice. We will have you drive for at least 3 minutes. Once those 3 minutes are up, if you feel comfortable you can stop. We will inform you once the 3 minutes have passed.

Here are the eye tracking glasses, you can put them on now. We need to calibrate them while you are wearing them so that they will provide the most accurate results. Please look at the "crosshair" on the projection screen in front of you.
(researcher will calibrate glasses at this time).

Now please look at the seat belt icon in the center console display.
(researcher will confirm the calibration at this time).

(press the red "record" button to start recording, on the ETG software)

Please try to disregard the glasses, and move as you normally would.

(move to the front co-driver seat of the car)

NEXT

Practice Trial

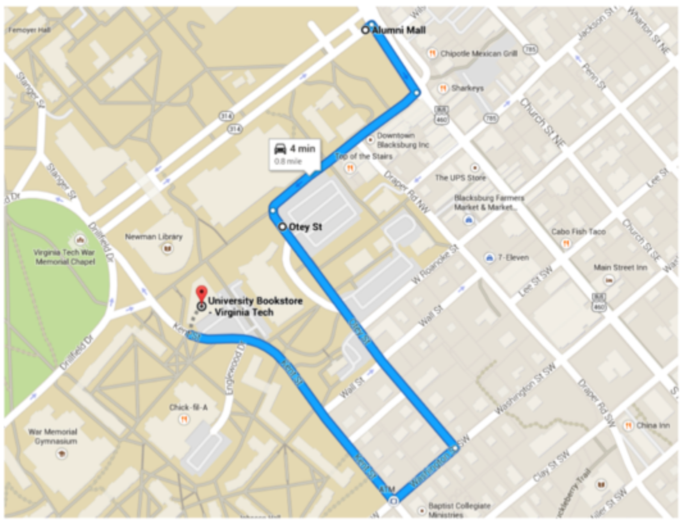
This is a practice trial. We want you to understand the task required and get a better idea of what the study will be. Feel free to ask questions at any point during this trial. If you have any questions, it's best to ask them all now. During the 3 test scenarios, you can not ask any questions rather we will pause at pre-determined times to ask questions.

Route Plan

We are now going to start the practice trial. Here is the route you will be following.

(show route).

Once you understand the route, you may place your hands on the wheel and foot on the pedal.



Start Driving

Please tell me when you're ready to begin.
Please begin driving as soon as the video starts.

(video starts)

Start driving now (if they haven't).

(observe the driver's behavior and remind her of manipulating any required controls such as pedals or turn signals)

What is your current speed?
(Do not give options and wait for the participants' answer. Only If you can't find option that matches the participants' answer, please read out the options)

- ○ Less than 20 mph
- ○ About 25 mph (20~30 mph)
- ○ About 35 mph (30~40mph)
- ○ About 45 mph (40~50 mph)
- ○ Greater than 50 mph

After each question, we want to know your level of confidence that you got the "What's your confidence on the answer that you gave, on a scale from 0 to 10?" 0 for no confidence and 10 for strong confidence.
(wait for their answer)

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

Please continue to drive. In this practice trial, you won't have more pauses. However, in your test trials, you may have more pauses while driving.

(video restarts)

(observe the driver's behavior and remind her of manipulating any required controls such as pedals or turn signals)

(video ends)

End of practice trial

Congratulations. You completed your practice.

When you finish each driving trial, we will have you evaluate the task you just performed. Here are a few questions developed by NASA. Again, remember that your task was driving. There are 6 questions about task load. More details can be found at each questions.

BACK NEXT

Scenario 1

Assign a participant ID first

* Required

Participant ID *

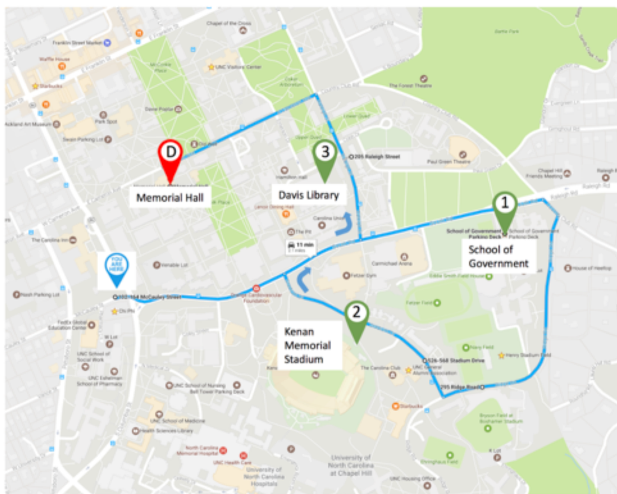
P1

Route Plan

Welcome to University of North Carolina! Here is the route for this trial. Look it over and let me know once you understand the route.

(show route)

Once you understand the route, you may place your hands on the wheel and foot on the pedal. We will give you voice instructions for turn by turn directions.



Start Driving

Please let me know when you are ready to begin. Remember to start driving as soon as the video begins.

(video starts)

Start driving now (if they haven't).

1st Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response.)

11 What is current speed limit of the road? *
(Do not give options and wait for the participants' answer. Only If you can't find option that matches the participants' answer, please read out the options)

- ◯ 15 mph
- ◯ 20 mph
- ◯ 25 mph
- ◯ 30 mph
- ◯ 40 mph

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

12 Are there any road signs (other than traffic lights) that require your reaction? If yes, what are those signs? *
(Do not give options and wait for the participants' answer. Only If you can't find option that matches the participants' answer, please read out the options)

- ☐ Yes (Stop)
- ☐ Yes (Speed Limit)
- ☐ Yes (No Left Turn)
- ☐ Yes (Roadwork Ahead)
- ☐ Yes (Pedestrian)
- ☐ No sign requiring my reaction
- ☐ Other: ______

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

13 Do you expect to pass this intersection before the traffic light turns into red?

- ◯ Yes
- ◯ No

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

2nd Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response.)

21 Which lane are you in? *

- ◯ Left lane
- ◯ Right lane
- ◯ Center lane

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

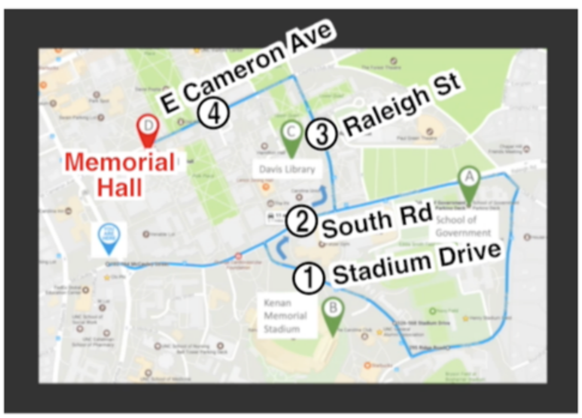
22 Do you need to make a turn at this intersection to get to the destination? *

- ◯ Yes, I need to turn left
- ◯ Yes, I need to turn right
- ◯ No

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

23 Which street are you on? Locate yourself on the map *



- ◯ 1. Stadium Drive
- ◯ 2. South Rd
- ◯ 3. Raleigh St
- ◯ 4. E Cameron Ave

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

Let me know once you are ready to begin driving again. You may have more pauses during this trial.

(remind them to start driving if they don't)

3rd Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response).

31 Are any pedestrians / bikes around you? (wait for the response...and if no, ask confidence and skip following questions). Select their locations from the given picture. *

- ☐ No pedestrians / bikes
- ☐ Yes (zone 1)
- ☐ Yes (zone 2)
- ☐ Yes (zone 3)
- ☐ Yes (zone 4)
- ☐ Yes (zone 5)
- ☐ Yes (zone 6)
- ☐ Yes (zone 7)
- ☐ Yes (zone 8)

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

32 Among zones you chose, Are any pedestrians / bikes heading into or currently on your path? (wait for the response...and if no, ask confidence and skip following questions) Select their current locations from the given picture. *

- [ ] No pedestrians / bikes
- [ ] Yes (zone 1)
- [ ] Yes (zone 2)
- [ ] Yes (zone 3)
- [ ] Yes (zone 4)
- [ ] Yes (zone 5)
- [ ] Yes (zone 6)
- [ ] Yes (zone 7)
- [ ] Yes (zone 8)

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

33 What do you expect to happen, if no action is taken? *

- ○ Collision
- ○ I would pass the pedestrian(s) / bike(s)
- ○ The pedestrian(s) / bike(s) would pass me
- ○ Nothing (No pedestrians heading into my path)

4th Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response. If they say "yes" to the first question, continue asking questions. If they say "no", just ask their confidence. Don't ask following two questions. Just select the option that says "No vehicle in front of me in my path").

41 Do you have a vehicle in front of you in your lane? *

- ◯ Yes
- ◯ No

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

42 Is that vehicle going to change lane or make a turn? *

- ◯ Yes, it is going to make turn
- ◯ Yes, it is going to change lanes
- ◯ No, it is not going to turn or change lane
- ◯ No vehicle in front of me in my lane

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

43 The gap between that vehicle and my car is going to be? *

- ◯ getting smaller
- ◯ getting larger
- ◯ remaining the same
- ◯ No vehicle in front of me in my lane

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

End of trial

Scenario 2

Assign a participant ID first

* Required

Participant ID *

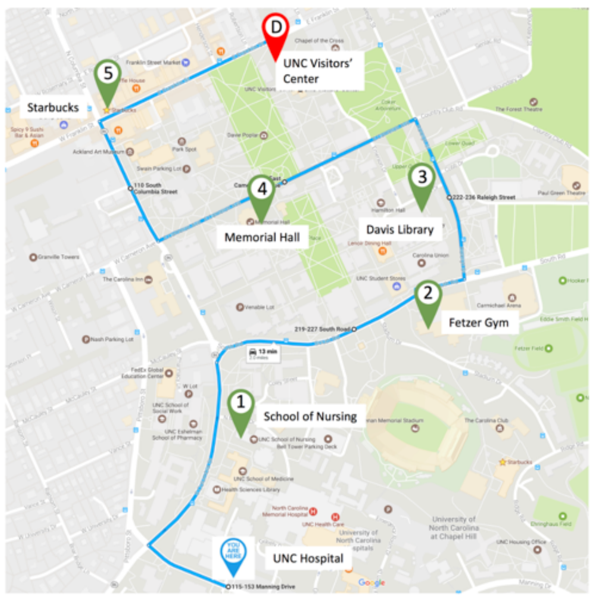
Choose

Route Plan

Welcome to University of North Carolina! Here is the route for this trial. Look it over and let me know once you understand the route.

(show route)

Once you understand the route, you may place your hands on the wheel and foot on the pedal. We will give you voice instructions for turn by turn directions.



Start Driving

Please let me know when you are ready to begin. Remember to start driving as soon as the video begins.

(video starts)

Start driving now (if they haven't).

1st Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response. If they say "no", no image will appear. Just ask their confidence. Don't ask following two questions. If they say "yes" to the first question, image will show up and continue asking questions).

11 Are any pedestrians / bikes around you? (wait for the response...and if no, ask confidence and skip following questions). Select their locations from the given picture. *

- [ ] No
- [ ] Yes (zone 1)
- [ ] Yes (zone 2)
- [ ] Yes (zone 3)
- [ ] Yes (zone 4)
- [ ] Yes (zone 5)

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

12 Among zones you chose, Are any pedestrians / bikes heading into or currently on your path? (wait for the response...and if no, ask confidence and skip following questions) Select their current locations from the given picture. *

- [ ] No
- [ ] Yes (zone 1)
- [ ] Yes (zone 2)
- [ ] Yes (zone 3)
- [ ] Yes (zone 4)
- [ ] Yes (zone 5)

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

13 What do you expect to happen, if you do not make any change? *

- ◯ Collision
- ◯ I would pass the pedestrian(s) / bike(s)
- ◯ The pedestrian(s) / bike(s) would pass me
- ◯ Nothing (No pedestrians heading into my path)

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

Let me know once you are ready to begin driving again. You may have more pauses during this trial.

(remind them to start driving if they don't)

2nd Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response.)

21 What is your current speed? *
(Do not give options and wait for the participant's answer)

- ◯ Less than 20 mph
- ◯ About 25 mph (20~30 mph)
- ◯ About 35 mph (30~40mph)
- ◯ About 45 mph (40~50 mph)
- ◯ Greater than 50 mph

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

22 You are currently traveling *

- ☐ Below the speed limit (< 5mph)
- ☐ At the speed limit (within +- 5mph)
- ☐ Above the speed limit (> 5mph)
- ☐ Other: ______

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

23 Do you expect to pass this intersection before the traffic light turns into red?

◯ Yes

◯ No

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

Let me know once you are ready to begin driving again. You may have more pauses during this trial.

(remind them to start driving if they don't)

3rd Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response. If they say "yes" to the first question, continue asking questions. If they say "no", just ask their confidence. Don't ask following two questions. Just select the option that says "No vehicle in front of me in my path").

31 Do you have a vehicle in front of you in your lane? *

◯ Yes

◯ No

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

32 Is that vehicle going to change lane or make a turn? *

◯ Yes, it is going to make turn

◯ Yes, it is going to change lanes

◯ No, it is not going to turn or change lane

◯ No vehicle in front of me in my lane

What's your confidence on the answer? *

33 The gap between that vehicle and my car is going to be? *

- ◯ getting smaller
- ◯ getting larger
- ◯ remaining the same
- ◯ No vehicle in front of me in my lane

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

Let me know once you are ready to begin driving again. You may have more pauses during this trial.

(remind them to start driving if they don't)

4th Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response.)

41 Which lane are you in? *

- ☐ Left lane
- ☐ Right lane
- ☐ Center lane

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

42 Do you need to make a turn at this upcoming intersection to get to the destination? *

- ◯ Yes, I need to turn left
- ◯ Yes, I need to turn right
- ◯ No

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	strong confidence

43 Which street are you on? Locate yourself on the map *

Locate yourself on the map

- 1. Raleigh St
- 2. E Cameron Ave
- 3. S Columbia St
- 4. E Franklin St

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

End of trial

Congratulations, you completed one of your driving trials.

Now we want you to evaluate the task load you just performed. Remember that your job was driving (getting to the destination safely).

NEXT

Never submit passwords through Google Forms.

Scenario 3

Assign a participant ID first

* Required

Participant ID *

Choose

Route Plan

Welcome to NC State University! Here is the route for this trial. Look it over and let me know once you are comfortable with it.

(show route)

Once you understand the route, you may place your hands on the wheel and foot on the pedal. We will give you voice instructions for turn by turn directions.

Start Driving

Please let me know when you are ready to begin. Remember to start driving as soon as the video begins.

(video starts)

Start driving now (if they haven't).

1st Pause

(video pauses)

Now we have a few questions for you.

11 What is the state of the traffic light (for you)? *

(read out the options)

- ◯ Green (including signals for turns)
- ◯ Red
- ◯ Yellow
- ◯ Flashing Red
- ◯ Flashing Yellow
- ◯ No traffic light for you

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

12 You're currently traveling *

- ○ Below the speed limit (< 5 mph)
- ○ At the speed limit (within +- 5 mph)
- ○ Above the speed limit (> 5 mph)

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

13 Do you expect to pass this intersection before the traffic light turns into red?

- ○ Yes
- ○ No

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

Let me know once you are ready to begin driving again. You may have more pauses during this trial.

(remind them to start driving if they don't)

2nd Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response. If they say "yes" to the first question, continue asking questions. If they say "no", just ask their confidence. Don't ask following two questions. Just select the option that says "No vehicle in front of me in my path").

21 Do you have a vehicle in front of you in your *

- ○ Yes
- ○ NO

What's your confidence on the answer? *

on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

22 Is that vehicle going to change lane or make a turn? *

- Yes, it is going to make turn
- Yes, it is going to change lanes
- No, it is not going to turn or change lane
- No vehicle in front of me in my lane

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

23 The gap between that vehicle and my car is going to be? *
Locate yourself on the map

- getting smaller
- getting larger
- remaining the same
- No vehicle in front of me in my lane

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

Let me know once you are ready to begin driving again. You may have more pauses during this trial.

(remind them to start driving if they don't)

3rd Pause

(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response. If they say "no", no image will appear. Just ask their confidence. Don't ask following two questions. If they say "yes" to the first question, image will show up and continue asking questions).

31 Which lane are you in? *

- Left lane
- Rigth lane
- Center lane

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong

32 Do you need to make a turn at this upcoming intersection to get to the destination? *

- Yes, I need to turn left
- Yes, I need to turn right
- No

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

33 Which street are you on? Locate yourself on the map *

- 1. Jeter Dr
- 2. Castes Ave
- 3. Jensen Dr
- 4. Dunn Ave

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

4th Pause

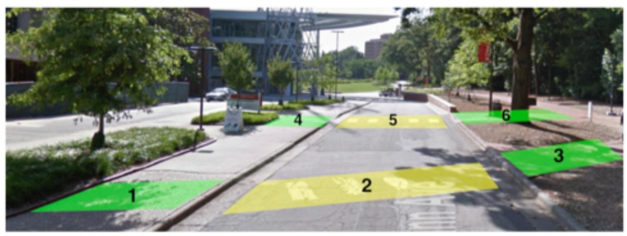
(video pauses)

Now we have a few questions for you.

(Read questions and Select appropriate response. If they say "no", no image will appear. Just ask their confidence. Don't ask following two questions. If they say "yes" to the first question, image will show up and continue asking questions).

41 Are any pedestrians / bikes around you? (wait for the response...and if no, ask confidence and skip following questions). Select their locations from the given picture. *

- ☐ No
- ☐ Yes (zone 1)
- ☐ Yes (zone 2)
- ☐ Yes (zone 3)
- ☐ Yes (zone 4)
- ☐ Yes (zone 5)
- ☐ Yes (zone 6)



What's your confidence on the answer? *
on a scale from 0 to 10

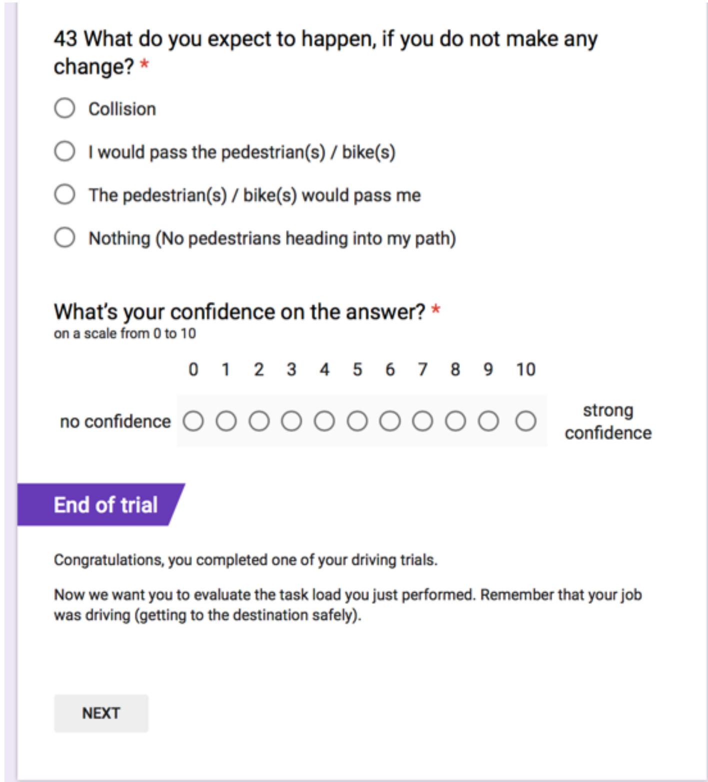
	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

42 Among zones you chose, Are any pedestrians / bikes heading into or currently on your path? (wait for the response...and if no, ask confidence and skip following questions) Select their current locations from the given picture. *

- ☐ No
- ☐ Yes (zone 1)
- ☐ Yes (zone 2)
- ☐ Yes (zone 3)
- ☐ Yes (zone 4)
- ☐ Yes (zone 5)
- ☐ Yes (zone 6)

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence



43 What do you expect to happen, if you do not make any change? *

- Collision
- I would pass the pedestrian(s) / bike(s)
- The pedestrian(s) / bike(s) would pass me
- Nothing (No pedestrians heading into my path)

What's your confidence on the answer? *
on a scale from 0 to 10

	0	1	2	3	4	5	6	7	8	9	10	
no confidence	○	○	○	○	○	○	○	○	○	○	○	strong confidence

End of trial

Congratulations, you completed one of your driving trials.

Now we want you to evaluate the task load you just performed. Remember that your job was driving (getting to the destination safely).

NEXT

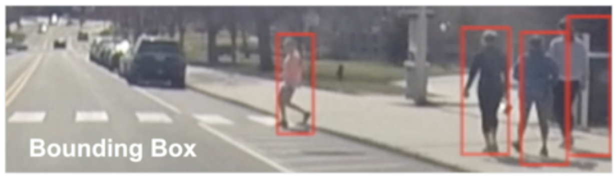
Appendix H. Post-test Survey

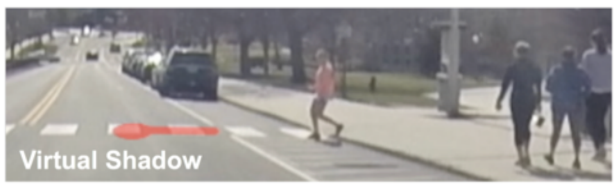
3. Post-Test Survey

(Ask questions in the driving simulator. Responses will be recorded by a microphone in the Eye Tracking Glasses)

Q1. Which interface design metaphor would you like more?

(show the pictures to the participant)





Q2. Could you tell me why you like that design metaphor more?

Q3. Would you give us any comments for design improvement?

Congratulations, you completed the entire study! Give me a second and I'll get you out of the simulator soon.

(get out of the simulator and press the red "record" button the ETG software, to end recording)

Would you take off the eye tracking glasses?

(guide the participants out of the simulator)

Thank you so much for your time! Have a nice day :)

SUBMIT