Determining the Impact of Augmented Reality Graphic Spatial Location and Motion on Driver Behaviors

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Abstract

While researchers have explored benefits of adding augmented reality graphics to vehicle displays, the impact of graphic characteristics have not been well researched. In this paper, we consider the impact of augmented reality graphic spatial location and motion, as well as turn direction, traffic presence, and gender, on participant driving and glance behavior and preferences. Twenty-two participants navigated through a simulated environment while using four different graphics. We employed a novel glance allocation analysis to differentiate information likely gathered with each glace with more granularity. Fixed graphics generally resulted in less visual attention and more time scanning for hazards than animated graphics. Finally, the screen-fixed graphic was preferred by participants over all world-relative graphics, suggesting that graphic spatially integration into the world may not always be necessary in visually complex urban environments like those considered in this study.

1. Introduction

Head-up displays (HUDs) with augmented reality (AR) graphics afford the opportunity to place information within users' field of view and to leverage novel methods of incorporating graphics into the surrounding environment. Optical see-through HUDs overlay computer-generated AR content onto see-through screens so that it is collocated with the real world. Collocation may assist drivers in maintaining their visual attention on the task, thus making it easier to extract display information simultaneously with driving-related information (e.g., lane markings, road signs, hazards). HUDs may reduce the time-cost of switching visual attention locations (Horrey & Wickens, 2004b; McCann, Foyle, et al., 1993; McCann, Lynch, et al., 1993), allowing drivers to spend more time with their eyes on the road (Medenica et al., 2011) and minimizing the load on short term memory (Hou et al., 2013). A significant body of research has examined the impact of HUD use on driver behaviors, particularly compared to traditional (head-down) displays. HUDs have been associated with improved lateral driving performance (Bolton et al., 2015; Horrey & Wickens, 2004a), longitudinal driving performance (Bolton et al., 2015), improved navigation (Bolton et al., 2015), spatial awareness (Tang et al., 2003), situational awareness (H. Kim et al., 2013; Skrypchuk et al., 2020), and lower self-reported mental workload (Häuslschmid et al., 2015; Liu & Wen, 2004; Smith, Streeter, et al., 2015). In addition, HUD use has been associated with faster response time for secondary tasks (Smith, Streeter, et al., 2015) as compared to traditional displays.

However, early research shows that people cannot simultaneously process the world and a screen-fixed display (McCann, Foyle, et al., 1993). Instead, the mind treats them as two separate images, incurring a cost of switching attention from a HUD to the real world and vice versa, even when the focal distance between stimuli and the real world is perfectly matched (Gabbard et al., 2018). HUDs may add visual demand due to additional information (Medenica et al., 2011) or cause important information in the real world to be missed (Sojourner & Antin, 1990). Drivers seem inclined to trust HUDs and may prefer to use them (H. Kim et al., 2013; Smith, Streeter, et al., 2015) even when the addition of AR cues is confusing (H. Kim et al., 2013). HUD use may attract drivers' visual attention toward the display (Bolton et al., 2015; Smith et al., 2017; Smith, Streeter, et al., 2015) and may not improve driving performance (Smith et al., 2017; Smith, Streeter, et al., 2015). Driving is carried out in a dynamic environment, meaning that there are risks involved with even the smallest of vehicles at slow speeds. Therefore, researchers must fully understand how the design of AR graphics changes behavior to ensure the safety of drivers and other road users.

1.1. AR Graphic Spatial Location

Broadly speaking, AR graphics can be described by their point of reference and associated motion. Point of reference indicates whether information provided by the display can be perceptually attached to the real *world* or to a *screen* (Gabbard et al., 2014). Current technology (e.g. aftermarket detachable screens and some vehicle windshields) supports screen-relative graphics that are seemingly attached to the *screen* (Gabbard et al., 2014). The majority of driving research exploring AR HUD graphics has used screen-fixed displays (e.g., Häuslschmid et al., 2015; Horrey & Wickens, 2004b; McCann, Foyle, et al., 1993; McCann, Lynch, et al., 1993; Smith et al., 2016, 2017; Smith, Doutcheva, et al., 2015; Smith, Streeter, et al., 2015; Sojourner & Antin, 1990).

As the enabling technology required to track and register graphics relative to locations off-screen improves, it may become possible to present AR graphics that are perceived by drivers as being attached to the *world*. World-registered graphics (also called *conformal* graphics) have long been thought to be the ideal AR display because AR graphic cues could appear as if they are actually part of the world. Correct spatial registration is associated with faster task completion time (Henderson & Feiner, 2009; Tang et al., 2003), increased task accuracy (Chintamani et al., 2009; Tang et al., 2003) and improved mental workload levels (Tang et al., 2003). Therefore, world-relative graphics may help drivers with spatial location tasks like navigation or maintaining vehicle position. Early studies have found that world-fixed graphics may result in a higher percentage of time looking towards the road center (Medenica et al., 2011) but do not necessarily improve spatial knowledge acquisition or workload (de Oliveira Faria et al., 2019). A world-fixed pedestrian notification system led to smoother braking performance and increased stopping distances to the pedestrian when compared to screen-fixed graphics (H. Kim et al., 2016). However, Merenda et al. compared near and far navigation using screen- and world-fixed graphics and found that there were tradeoffs, such that increased precision afforded by world-fixed graphics may also result in additional processing time (Merenda et al., 2018).

1.1.1. Information Visualization

Translating graphics from a 2D canvas onto a 3D space influences the location, shape, and even abstraction needed to convey information, requiring a fundamental shift in graphic design. AR graphics can be overlaid onto the world using two primary visualization techniques: localization (added to the world) or integration (embedded into the world) (Grubert et al., 2016). Consider an arrow, one of the most commonly employed navigation cues, which has a clear meaning in 2D spaces. When translating navigation information to world-relative graphics, the information can be *localized* by simply placing more 2D graphics (arrows) within the world in the same form, like a digital but personalized sign. Signs (even near the road), however, are still separate from the task itself, meaning that those using the sign must still process the meaning and determine the relevant spatial location. The main benefit of this type of spatial location is that it reduces the physical distance between the graphic (arrow) and the task (road). However, the same graphic could also be *integrated* to appear as if it is part of the world, for example, painting an arrow onto the road itself.

AR graphic integration retains the meaning of the graphic and reduces distance between the graphic and driving task even more than localization, yet integration then requires a fundamental change in form. From one angle, the graphic is clearly an arrow, but from the other perspectives, the shape of the arrow may be elongated in such a way that, removed from the context of the road, it would not be perceived as an arrow. As drivers move within the world, the shape of the arrow would also necessarily change depending on their position relative to the road and overlaid arrow. These changes in shape are an inherent feature to real objects in a 3D space, and people process the shapes to determine the expected 3D form based on prior knowledge of the space or other similar experiences. This change necessarily abstracts the information, but couples graphics so tightly that the time and effort required to spatially locate the information (e.g., identify the exact turn while driving) can theoretically be reduced. This is a key potential benefit of AR graphics, but due to technical limitations in AR rendering to date, the impact of information abstraction to allow for spatial integration has not yet been well-studied.

1.2. AR Graphic Motion

Regardless of point of reference, AR graphics can also be *fixed* in one place or *animated*, with the graphic moving relative to its point of reference (Merenda et al., 2018). Most research to date has employed fixed graphics, and little work has been done to understand tradeoffs of using animated graphics. Gottlieb et al. found that screen-animated graphics (e.g., contextual displays that show or hide information as needed) may have unintended negative consequences, likely due to a surprised response when the graphics change (Gottlieb et al., 2018). Yet, animated displays may be well-suited to capturing and directing attention for time sensitive tasks. Using motion can draw attention and that may be useful for tasks requiring a time-sensitive response because the onset of motion captures attention (Abrams & Christ, 2003). Therefore, graphic motion could be used to direct attention to relevant hazards or navigation cues. The most common world-animated graphic studied for use in vehicles is that of a virtual car, which is a promising interface for in-vehicle navigation (Pampel et al., 2019; Topliss et al., 2018). However, a world-animated dynamic pedestrian identification system was more distracting and interfered with situational awareness as compared to a world-fixed virtual shadow (H. Kim & Gabbard, 2019).

1.3. Research Questions

These world- and screen-relative points of reference coupled with the presence of animation (or lack thereof) may impact driver behaviors and, to our knowledge, have received little attention from researchers, with only Merenda's 2018 study accounting for both AR graphic registration location and associated motion within the study design (Merenda et al., 2018). However, these graphic characteristics merit further exploration because they may impact driving or glance behaviors. Prior to widespread implementation of new AR graphics into vehicles, we must understand the implications of drivers using different graphic types. In this work, we examined the impact of screen-fixed, world-fixed, and two different world-animated AR graphics on participants' glance and driving behaviors as they navigated through a series of turns dictated by the navigational systems and gathered self-reported data about their experience. We aimed to answer the following questions:

- **RQ1**: How do different types of AR graphics impact drivers' performance in a navigation task?
- **RQ2**: How does the presence of graphic animation change glance and driving behaviors?

2. Method

2.1. Participants

In total, 31 participants signed up for the study, but almost 1/3 of the participants dropped out due to simulator sickness. Therefore, a total of 22 participants completed the study and were included in subsequent analyses. Thirteen men (mean: 20.3 years) and nine women (mean: 20.4 years) who drive regularly in the US completed in the study. Participants had a US driver's license for longer than 1 year (mean: 4.6 years) and drove an average of 7,918 miles per year. All participants reported normal or corrected-to-normal vision. 100% of these participants reported using smart phones and 68% specifically mentioned using smart phones or built-in vehicle displays for navigation purposes. No participants regularly drove a car with AR HUDs installed.

2.2. Equipment

We used National Advanced Driving Simulator MiniSim software to develop a visually rich, urban environment. Participants drove our medium fidelity, fixed-base driving simulator with a curved projection (94° field of view, 3m projection distance) displaying the simulated road scene (Gabbard et al., 2019). We fitted the simulator with a Pioneer CyberNavi HUD (3m focal depth) with conformal AR graphic capability attached to a moveable arm. Custom software integrated our driving simulation software with AR HUD rendered graphics, providing a real-time, world-registered AR HUD. We used SensoMotoric Instruments (SMI) eye tracking glasses and iView ETG 2.6 software to record gaze location for each participant and analyzed glances with SMI BeGaze 3.6.40 software. The glasses sampled at 60 Hz and recorded audio, participants' eyes, and a world-facing (first person) camera view.

2.3. Procedure

After participants consented to participate (IRB# 17-239) and completed a demographic survey, we fitted them with eye tracking glasses. Participants adjusted the simulator driver's seat to their preferred position before performing a 5-minute familiarization drive in the simulator. We then aligned the HUD to accommodate participants of varying height, seat position preference, and general posture.

During data collection, each participant completed a series of four drives (counterbalanced), with each drive including a single display condition: screen-fixed (SF), world-fixed (WF), world-animated 1 (WA1), and world-animated 2 (WA2). These graphics are described in more detail in section 2.4. Each drive lasted 6-12 minutes, after which participants filled out questionnaires and rested, if needed. Within a drive, participants drove through a single pre-determined urban route with a visually rich environment including buildings, vehicles, road signs, and were instructed to attend to oncoming traffic and cross traffic. Our route included eight 90° turns: four right and then four left, all of which were cued by the navigation system. Half of the turns within a drive included cross traffic which occurred during turns 2, 3, 5, and 6. We did not expose the participants to any of the HUD navigational cues prior to the experiment to mimic the first exposure to new graphics and a worst-case scenario of how novel graphics might impact drivers on the road. In total, the experiment took approximately 2 hours and participants were compensated $10 for their time.

2.4. AR Graphics

We developed four graphics to guide navigation along the route (Figure 1), all of which appeared when the driver was 492 feet from the intersection of the next turn. All graphics were visible for the full 492 feet and all turns were in sight at the graphic onset. Because the world-relative graphics in this study were integrated into the world, the form of the world-relative graphics necessarily changed as drivers (and animated graphics) moved within the world. While the information conveyed was the same and was available for the same amount of time, integrating the world-relative graphics into the world necessarily abstracted the graphic form. This abstraction is an artifact of integrating AR graphics into the world, where in place of words or familiar symbols, we might expect highlighted objects (e.g., the road) or digitally generated objects (e.g., virtual cars).

First, a screen-fixed (SF) 2D arrow, modeled after current widely available center-console and HUD navigation systems, provided a left or right indication and was presented at a fixed position on the HUD. Our second graphic type was a world-fixed (WF) arrow, which was fixed on the road and blue in color, similar to AR navigation concepts used in previous research (Bauerfeind et al., 2021; Bolton et al., 2015; Medenica et al., 2011; Merenda et al., 2018).

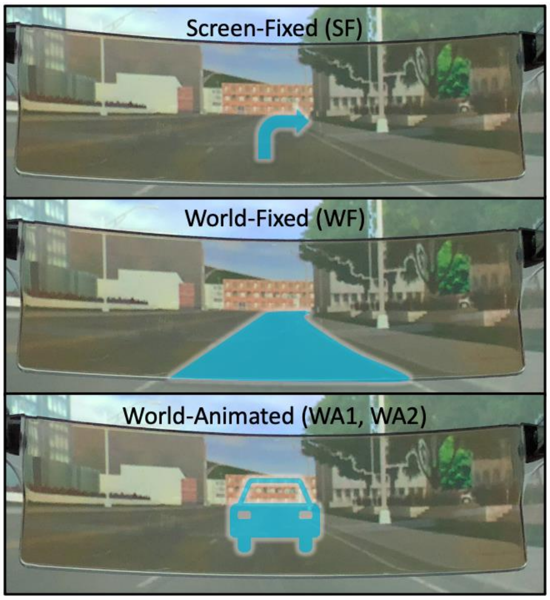

Figure 1: Representations of the AR HUD graphics that we employed.

We also developed two world-animated graphics (WA1 and WA2) that presented a 3D and world-registered “virtual car” in front of the participant, similar to previous world-animated “virtual cars” (Pampel et al., 2019; Topliss et al., 2018). For each WA condition, the virtual car drove at a 75-foot lead distance (regulated by the speed of participants’ simulated vehicles) and appeared in front of the participant 492 feet from each turn with a flashing turn signal indicating the turn direction. While WA graphics behaved the same while approaching turns, their behavior during turns was slightly different. Specifically, WA1 appeared, drove forward, slowed while approaching the turn and ultimately made the left or right turn independent of participants’ own-car position. When WA1 turned, it necessarily drove out of the field of view of the HUD. Conversely, as the WA2 virtual car approached the turn, it stopped at the intersection until participants “absorbed” or drove through the waiting virtual car.

2.5. Measures

Existing display assessment methods have not been validated for use with AR HUDs. Indeed, common guidelines such as those developed by the National Highway Traffic Safety Administration (NHTSA) (NHTSA, 2012) may not fully capture the benefits or downfalls of AR HUD use in vehicles (Smith et al., 2016). For that reason, we directly examined driving performance, glance behaviors, and self-reported measures to assess the impact of graphic type and HUD use on participants. We limited our analyses to the data corresponding to 492 feet of straight road immediately after the onset of the navigation cue, but prior to the beginning of the turn, similar to previous research (Bauerfeind et al., 2021). Lateral position was determined relative to lane center according to SAE J2944 10.1.1.1 and longitudinal vehicle control was captured through speed variation and vehicle deceleration.

Glance behavior refers to driver glance allocation to different areas of interest (AOIs) while driving. A single glance is composed of a series of saccades and fixations within one specific AOI (e.g. the road). Some of the most commonly used metrics for assessing driving focus on glance frequency and duration (Cotter et al., 2008) and the percentage of glance time fixated in the road center (Medenica et al., 2011; Victor et al., 2005) or the entire road, including peripheral areas (Seppelt et al., 2017). When using head-worn glasses or animated graphics, the centrality of different AOIs may change, so rather than calculating glance measures based on centrality, we developed a dynamic AOI coding scheme that captured participants' visual scan patterns to areas relevant to driving (Figure 2).

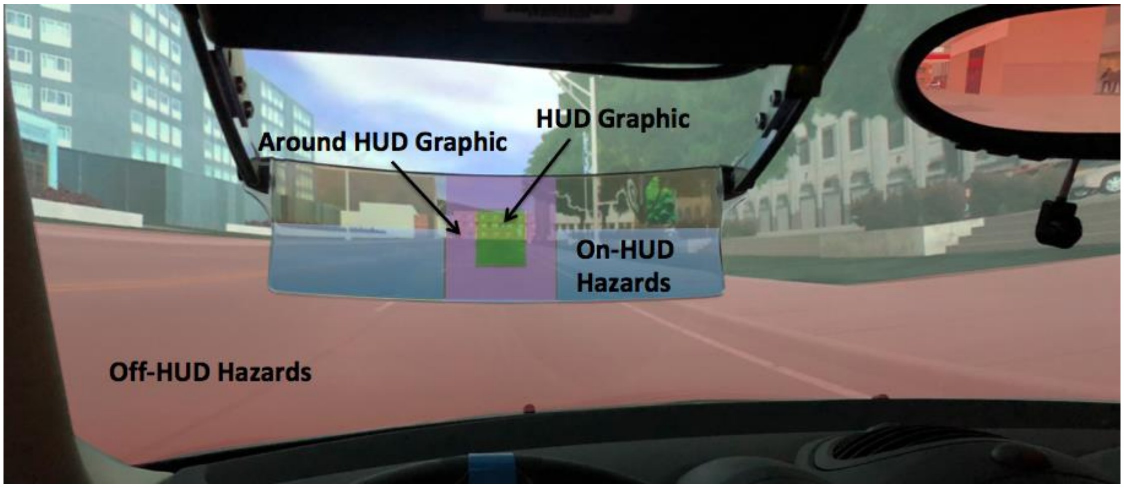

Figure 2: Detailed AOI glance coding scheme: HUD graphic (green), around HUD graphic (purple), on-HUD hazards (blue), off-HUD hazards (red).

To account for AR graphics overlapping with the road, we segmented the HUD into three AOIs: "HUD graphic", "around HUD graphic", and "on-HUD hazards". HUD graphic included all fixations where the driver looked directly at the graphic. However, occasionally the HUD graphic occluded the roadway ahead, and may have caused participants to look at locations adjacent to the HUD graphic (around HUD graphic). Because the HUD was positioned to afford world-registered graphics overlaid onto the roadway, participants also looked through the HUD, but not necessarily near the graphic, in order to check for traffic or other hazards (on-HUD hazards). In addition to these AOIs embedded within the HUD, we also analyzed check glances towards potential cross traffic, mirrors, and other lanes which encompassed all potential hazards that were visible without looking through the HUD ("off-HUD hazards").

We collected NASA TLX scores after completion of each drive (Hart & Staveland, 1988). At the end of the study, participants ranked the graphic types in order of preference and provided additional qualitative feedback.

3. Data Analysis

We conducted a mixed-effects ANOVA to analyze all driving and glance behaviors. The independent measures in this study included graphic type (SF, WF, WA1, WA2), turn direction (right, left), and traffic presence (present, not present). We used gender as a blocking variable for analysis. Prior to analysis, we checked the residuals of the model for normality and log transformed data with non-normal residuals. All data could be adequately modeled with either original data or log-transformed data. All statistics were conducted using JMP Pro 14. Alpha was set at 0.05, and significant values are denoted in tables with bold font and asterisks (*** when $p<.001$, ** when $p<.01$, and * when $p<.05$). Cohen's d is reported to indicate effect size for significant results. A subset of this data was previously published with an analysis of screen-fixed and world-fixed arrows only (Gabbard et al., 2019).

4. Results

4.1. Driving Behaviors

There were main effects of graphic type, traffic, and turn direction on participants' mean lane position (Table 1). Participants drove an average of 0.55 feet to the right of the lane center when traffic was present but only 0.15 feet to the right of lane center without traffic ($p<.001$, $d=.60$). When making right turns, participants drove further towards the right side of the lane ($\mu=.53$ft) than when making left turns ($\mu=.17$ft, $p<.001$, $d=.52$). Post hoc Tukey testing showed no pairwise significant differences between graphic types.

Participants exhibited higher standard deviation of lane position when traffic was present at the turn (μ=1.11ft) as compared to when there was no traffic present (μ=.94ft, *p* <.001, *d*=.34). As participants approached left turns, standard deviation of lane position (μ=1.27ft) was higher than their approach to right turns (μ=.79ft, *p* <.001, *d*=1.14).

Table 1: Mixed-effect ANOVA Results for Vehicle Control Measures

	Mean Lane Position		***St. Dev. of Lane Position***	
Source	*F* Ratio	*p*-value	*F* Ratio	*p*-value
Graphic Type	*F*(3,662)=2.87	**0.036***	*F*(3,662)=.54	0.653
Gender	*F*(1,20.0)=.85	0.368	*F*(1,20.1)=3.24	0.087
Traffic	*F*(1,662)=61.9	**<.001*****	*F*(1,662)=19.7	**<.001*****
Turn Direction	*F*(1,662)=46.3	**<.001*****	*F*(1,662)=228	**<.001*****
Graphic Type*Gender	*F*(3,662)=1.21	0.306	*F*(3,662)=.14	0.933
Graphic Type*Traffic	*F*(3,662)=1.90	0.128	*F*(3,662)=.23	0.876
Graphic Type*Turn Direction	*F*(3,662)=.36	0.784	*F*(3,662)=1.54	0.203
	St. Dev. of Vehicle Speed		***Peak Deceleration***	
Source	*F* Ratio	*p*-value	*F* Ratio	*p*-value
Graphic Type	*F*(3,662)=2.04	0.107	*F*(3,662)=1.45	0.227
Gender	*F*(1,20.1)=.036	0.851	*F*(1,20.0)=.67	0.424
Traffic	*F*(1,662)=11.7	**<.001*****	*F*(1,662)=13.0	**<.001*****
Turn Direction	*F*(1,662)=50.3	**<.001*****	*F*(1,662)=114	**<.001*****
Graphic Type*Gender	*F*(3,662)=.216	0.885	*F*(3,662)=.22	0.885
Graphic Type*Traffic	*F*(3,662)=2.39	0.067	*F*(3,662)=.61	0.607
Graphic Type*Turn Direction	*F*(3,662)=.28	0.842	*F*(3,662)=1.07	0.360

When traffic was present, participants varied their speed more (μ=8.87mph) than when traffic was not present (μ=8.08mph, *p*<.001, *d*=.26). When making right turns, participants' standard deviation of vehicle speed (μ=9.30mph) was higher than when making left turns (μ=7.65mph, *p* <.001, *d*=.54).

The presence of traffic was associated with lower peak decelerations (μ=8.76mph) than when traffic was not present (μ=10.0mph, *p*<.001, *d*=.27). When turning right (μ=11.2mph), participants decelerated more than when making left turns (μ=7.52mph, *p*<.001, *d*=.81).

4.2. Glance Behaviors

There were order effects within the glance behavior data and therefore we included order effects in the model (Table 2).

Table 2: Mixed-effect ANOVA results for maximum and average glance durations toward the HUD graphic

	Log of maximum HUD Graphic Glance Duration	**Log of average HUD Graphic Glance Duration**

Source	*F* Ratio	*p*-value	*F* Ratio	*p*-value
Graphic Type	*F*(3,627)=62.9	**<.001*****	*F*(3,628)=42.4	**<.001*****
Gender	*F*(1,20.0)=.001	0.981	*F*(1,20.1)=.061	0.807
Traffic	*F*(1,624)=1.35	0.245	*F*(1,624)=1.10	0.295
Turn Direction	*F*(1,626)=.13	0.715	*F*(1,626)=.87	0.351
Graphic Type*Gender	*F*(3,627)=.14	0.934	*F*(3,628)=.18	0.908
Graphic Type*Traffic	*F*(3,624)=2.45	0.063	*F*(3,624)=1.21	0.305
Graphic Type*Turn Direction	*F*(3,625)=1.30	0.274	*F*(3,626)=.90	0.439
Relative Graphic Order	*F*(3,627)=10.8	**<.001*****	*F*(3,628)=10.0	**<.001*****

SF graphics (μ=1.171s) resulted in the shortest maximum HUD graphic glance duration in seconds (s) relative to all other graphic types with a large effect size for all (WF: μ=3.328s, *p*<.001, *d*=1.50; WA1: μ=2.632s, *p*<.001, *d*=.980; WA2: μ=3.260s, *p*<.001, *d*=1.298). WA1 was associated with shorter maximum HUD graphic glance durations than WA2 (*p*=.039, *d*=0.318). Participants' average glance duration at the HUD graphic was shortest when using the screen-fixed arrow (μ=0.706s) relative to all other graphic types (WF: μ=1.478s, *p*<.001, *d*=1.123; WA1: μ=1.477s, *p*<.001, *d*=.920; WA2: μ=1.722s, *p*<.001, *d*=1.141).

The fourth HUD graphic (μ=2.359s) experienced was associated with lower average HUD glance durations than earlier trials (1: μ=2.484s, *p*<.001, *d*=.596; 2: μ=2.737s, *p*<.001, *d*=.547; 3: μ=2.790s, *p*<.001, *d*=.493). The last HUD graphic (μ=1.102s) resulted in shorter average durations as compared to previous trials (1: μ=1.411s, *p*<.001, *d*=.593; 2: μ=1.398s, *p*<.001, *d*=.475; 3: μ=1.461s, *p*<.001, *d*=.505).

Table 3: Mixed-effect ANOVA results for the percentage of time that participants looked at each AOI

	Percentage of Time looking at HUD graphic only		**Log of percentage of time looking at off-HUD hazards**	
Source	***F* Ratio**	***p*-value**	***F* Ratio**	***p*-value**
Graphic Type	*F*(3,626)=92.6	**<.001*****	*F*(3,627)=45.6	**<.001*****
Gender	*F*(1,20.0)=.002	0.962	*F*(1,19.9)=.96	0.338
Traffic	*F*(1,624)=3.76	0.053	*F*(1,624)=11.2	**<.001*****
Turn Direction	*F*(1,625)=1.33	0.249	*F*(1,625)=.007	0.934
Graphic Type*Gender	*F*(3,626)=1.89	0.130	*F*(3,627)=1.86	0.136
Graphic Type*Traffic	*F*(3,624)=.24	0.871	*F*(3,624)=.76	0.515
Graphic Type*Turn Direction	*F*(3,625)=1.67	0.173	*F*(3,625)=.43	0.731
Relative Graphic Order	*F*(3,627)=7.96	**<.001*****	*F*(3,627)=11.2	**<.001*****
	Log of percentage of time looking at on-HUD hazards		**Log of percentage of around time looking around HUD Graphic**	
Source	***F* Ratio**	***p*-value**	***F* Ratio**	***p*-value**
Graphic Type	*F*(3,627)=55.5	**<.001*****	*F*(3,627)=11.0	**<.001*****
Gender	*F*(1,20.1)=1.22	0.282	*F*(1,20.1)=.082	0.778
Traffic	*F*(1,624)=121	**<.001*****	*F*(1,624)=7.67	**0.006****
Turn Direction	*F*(1,626)=11.7	**<.001*****	*F*(1,625)=10.4	**0.001****
Graphic Type*Gender	*F*(3,627)=3.56	**0.014***	*F*(3,627)=2.56	0.054

Graphic Type*Traffic	*F*(3,624)=29.0	**<.001*****	*F*(3,624)=4.35	**0.005***
Graphic Type*Turn Direction	*F*(3,625)=2.06	0.104	*F*(3,625)=.52	0.672
Relative Graphic Order	*F*(3,628)=5.75	**<.001*****	*F*(3,627)=3.17	**0.024***

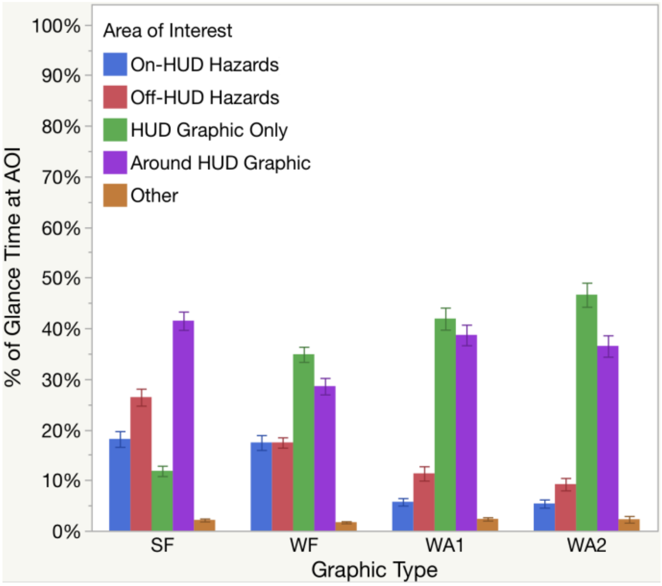

Figure 3: Use of the four graphic types resulted in different allocations of glance time across the five areas of interest. SF differed the most from other graphic types.

WF was associated with participants spending less time looking around the HUD graphic as compared to SF and WA1. When using SF, participants spent more time looking around the HUD graphic than when using WF or WA2. Participants allocated between 29% and 41% of glance time looking around the HUD graphic. Participants spent more time looking around the HUD graphic when no traffic was present (μ=38%) as compared to the turns that did have traffic (μ=34%, *p*=.006, *d*=.22) though the effect size was small. Participants looked around the HUD graphic for a higher percentage of time when making right turns (μ=39%) rather than left turns (μ=34%, *p*=.001, *d*=.25). The presence of traffic more strongly affected the percentage of time participants looked around the SF and WF HUD graphics than WA1 and WA2.

The last HUD graphic experienced by participants was associated with a lower percentage of time spent looking at the HUD graphic (μ=29.89%) relative to previous trials (1: μ=34.58%, *p*<.001, *d*=.534; 2: μ=33.02%, *p*=.003, *d*=.411; 3: μ=37.43%, *p*<.001, *d*=.452). The last HUD graphic experienced by participants resulted in a higher percentage of time looking at off-HUD hazards (μ=20.77%) when compared to previous trials (1: μ=12.29%, *p*<.001, *d*=.684; 2: μ=16.44%, *p*<.001, *d*=.449; 3: μ=14.99%, *p*<.001, *d*=.422). The percentage of time that participants looked at on-HUD hazards while using the last graphic type (μ=9.47%) was different than the first (μ=12.30%, *p*=.029, *d*=.334) or third (μ=12.72%, *p*<.001, *d*=.466) graphic types. Participants looked at the HUD graphic least when using SF (μ=12%), and most when using WA2 (μ=47%). SF use resulted in participants looking at off-HUD hazards for the highest percentage of time (μ=26.40%) relative to all other graphic types (WF: μ=17.44%, *p*<.001, *d*=.748; WA1: μ=11.34%, *p*<.001, *d*=1.024; WA2: μ=9.21%, *p*<.001, *d*=1.263).

WF also resulted in a higher percentage of time spent looking at off-HUD hazards as compared to WA2 (*p*<.001, *d*=.515). Fixed graphics (SF: μ=18.13%, WF: μ=17.44%) were associated with a higher percentage of time looking at on-HUD hazards as compared to the animated graphics (WA1: μ=5.72%, WA2: μ=5.38%). Graphic animation was associated with a lower percentage of time looking at on-HUD hazards (*p*<.001 for all) with a large effect size for all pairwise comparisons (SF/WA1: *d*=1.005; SF/WA2: *d*=1.074; WF/WA1: *d*=.982; SF/WA2: *d*=1.052). The no-traffic condition was associated with a higher percentage of glance time at off-HUD hazards (μ=18%) compared to the traffic condition (μ=14%, *p*=.001, *d*=.26). Turns with traffic were associated with a higher percentage of glances at on-HUD hazards (μ=17%) compared to turns with no traffic (μ=6%, *p*<.001, *d*=.86). When turning left, participants looked at on-HUD hazards for a higher percentage of time (μ=13%) than when turning right (μ=10%, *p*<.001, *d*=.27), though the effect size is small. There was an interaction effect of graphic type and gender on the percentage of time that participants spent looking at on-HUD hazards. Screen-fixed elicited a different percentage of time looking at on-HUD hazards in male and female participants. The presence of traffic had an unequal impact on the percentage of time that participants spent looking at on-HUD hazards across graphic types. When traffic was present, participants using screen-fixed and world-fixed graphics spent a higher percentage of time looking at on-HUD hazards than without traffic.

4.3. NASA TLX

There were no order effects within the NASA TLX data and therefore we excluded order from the model. We found a main effect of graphic type on all NASA TLX sub-scores and RAW TLX (Table 4, Figure 4).

Table 4: Mixed-effect ANOVA NASA TLX Results. Mean values for graphic types included in the table.

Source	***F* Ratio**	***p*-value**	**SF**	**WF**	**WA1**	**WA2**
Mental Demand						
Graphic Type	*F*(3,60.0)=8.15	**<.001*** **	11.68	23.73	29.36	35.46

Gender	*F*(1,20.0)=.65	0.431				
Graphic Type*Gender	*F*(3,60.0)=.25	0.864				
Physical Demand						
Graphic Type	*F*(3,60.0)=3.55	**0.020***	8.91	10.41	12.23	17.00
Gender	*F*(1,20.0)=.41	0.530				
Graphic Type*Gender	*F*(3,60.0)=.52	0.670				
Temporal Demand						
Graphic Type	*F*(3,60.0)=5.07	**0.003****	8.32	8.50	15.73	15.09
Gender	*F*(1,20.0)=.02	0.888				
Graphic Type*Gender	*F*(3,60.0)=2.82	**0.047***				
Effort						
Graphic Type	*F*(3,60.0)=11.6	**<.001*****	12.64	21.09	28.96	38.55
Gender	*F*(1,20.0)=.15	0.705				
Graphic Type*Gender	*F*(3,60.0)=1.14	0.340				
Frustration						
Graphic Type	*F*(3,60.0)=6.71	**<.001*****	6.91	14.05	22.50	27.59
Gender	*F*(1,20.0)=2.64	0.120				
Graphic Type*Gender	*F*(3,60.0)=1.23	0.306				
Performance						
Graphic Type	*F*(3,60.0)=3.15	**0.031***	84.73	80.36	79.23	67.50
Gender	*F*(1,20.0)=4.82	**0.040***				
Graphic Type*Gender	*F*(3,60.0)=.96	0.419				
Raw TLX						
Graphic Type	*F*(3,60.0)=13.2	**<.001*****	10.62	16.24	21.59	22.70
Gender	*F*(1,20.0)=1.91	0.182				
Graphic Type*Gender	*F*(3,60.0)=1.60	0.199				

SF resulted in lower reported demand than WA2 (mental: *p*<.001, *d*=1.45; physical: *p*=.017, *d*=.939; effort: *p*<.001, *d*=1.70; frustration: *p*=.001, *d*=1.23; performance: *p*=.022, *d*=.908; raw TLX: *p*<.001, *d*=1.815). SF also received lower reported mental demand (*p*=.004, *d*=1.099), temporal demand (*p*=.017, *d*=.939), effort (*p*=.003, *d*=1.135), frustration (*p*=.009, *d*=1.013), and raw TLX (*p*<.001, *d*=1.258) when compared to WA1. Participants reported that WF resulted in lower effort (*p*=.002, *d*=1.78), frustration (*p*=.046, *d*=.820), and raw TLX (*p*=.001, *d*=1.217) than WA2.

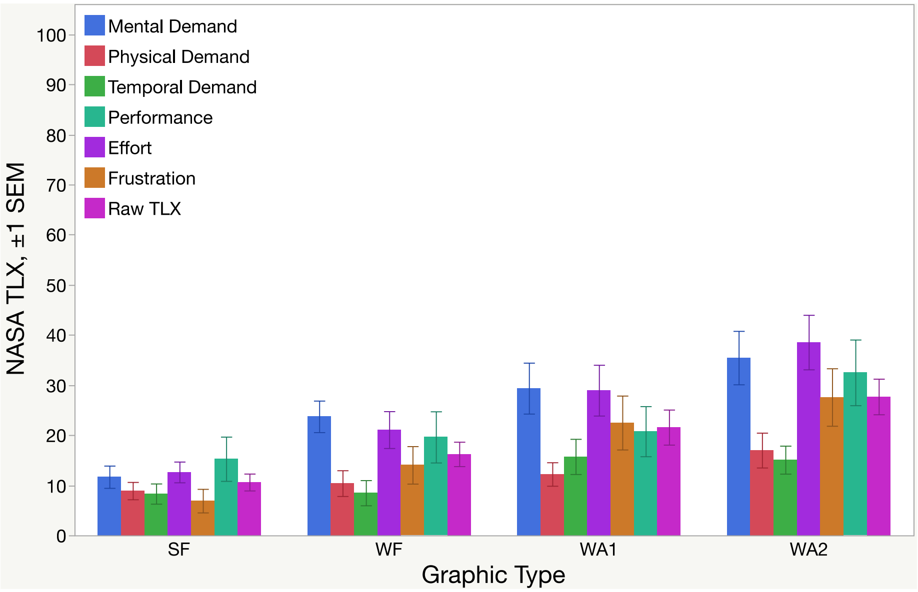

Figure 4: Screen-fixed graphics resulted in the lowest mental demand, with the animated graphics resulting in the highest mental demand. (Note: Is this graph, performance has been reverse-coded such that higher scores indicate lower perceived performance to maintain consistency with other NASA TLX sub-scores.)

Post hoc testing showed an interaction effect between graphic type and gender on participants' reported temporal demand. Male and female participants responded differently to WA1 and WA2 graphics. Female participants also reported worse performance (μ=67.7) than male participants (μ=85.1, *p*=.040, *d*=1.00).

4.4. Preferences

Most participants preferred the SF graphic and WA2 was the least preferred graphic (Figure 5).

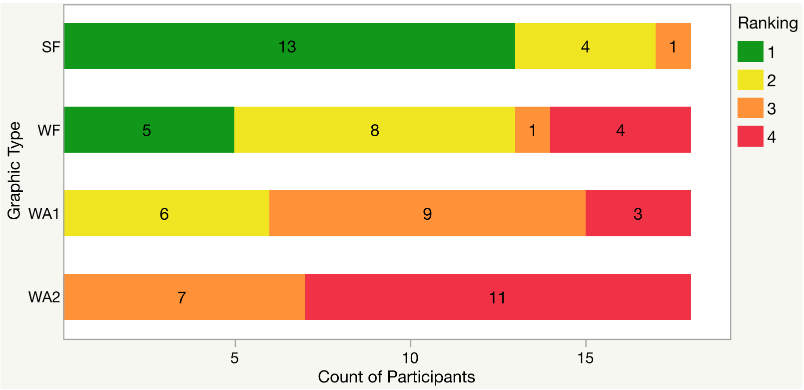

Figure 5: The screen- and world-fixed graphics were most preferred by participants. Four participants did not complete the preference portion of the survey, so we included data only from the remaining 18 participants.

5. Discussion

5.1. Glance Behavior

Ideal driver glance allocation differs based on the driving environment and driver goals (Recarte & Nunes, 2003). Yet, good driving practices suggest drivers should continuously scan many areas of interest because each can present important and relevant information. AR graphics may also require separate visual processing from the real world (McCann, Foyle, et al., 1993), even when focal depth is matched (Gabbard et al., 2018). Therefore, an optimal graphic likely requires few glances of short duration in the direction of the graphic. AR graphics that require the lowest percentage of time looking at the HUD and maximize time scanning for hazards most likely support optimal glance allocation while driving.

We found different graphic types resulted in wide variations in participants' glance patterns with screen-fixed graphics resulting in fewest and shortest glance durations. While the same type of information was being provided for all graphics, it is possible that the "cognitive distance", or the effort required to process and spatially orient information (S. Kim & Dey, 2009; Merenda et al., 2018), was larger for the world-relative graphics than the screen-relative graphics. Mentally fusing the world-relative graphics with the surrounding environment likely required participants to switch between the graphic and environment, which may exacerbate perceptual issues with using AR (Gabbard et al., 2018). Conversely, participants only needed to perceive the screen-relative image to extrapolate the meaning of the graphic and may have found screen-relative graphics easier to differentiate from objects in the simulated driving environment than those that were world-relative. Indeed, simple, screen-fixed designs may indeed be effective in certain contexts. It is possible that participants allocated more visual attention to hazard scanning rather than looking at the graphic and preferred screen-relative graphics because they have more practice using screen-relative graphics for navigation tasks in their current navigation systems.

The world-fixed graphic may have also caused longer maximum HUD graphic glances because it filled up most of the driving lane laterally, and therefore took up more space in participants' field of view than WA1 or WA2. The driving lane is an area that naturally requires frequent glances, as this is the area in which forward collisions would occur, and any hazard in this space must be responded to quickly. Therefore, by placing a fixed graphic in this area, we forced drivers to continue to look at or through the graphic as they checked the forward road scene for hazards. Another possible explanation for participants' extended glance durations and percentage of time looking towards world-relative graphics could be lagging or imperfect registration in the world, causing participants to rectify the differences via additional cognitive processing. However, this was not noted by researchers or anecdotally reported by participants. In addition, participants made comments suggesting that they anthropomorphized the world-animated graphics by assigning a gender to the object (e.g. "should I go around *him*?"). We expect that the type of world-animated graphic (e.g. virtual car) may have set participants' expectations for graphic behaviors (e.g. drive forward in the lane), and therefore any behavioral deviations from participants' expectations may have required additional processing to understand the meaning of the cues.

Different types of fixed and animated graphics may elicit different glance behaviors from drivers, and ultimately the degree to which graphics' demand attention may be specific to an animated/non-animated HUD graphic design. Thus, researchers must continue to explore the implications of graphic behavior on drivers' glance behaviors. Keeping AR HUD graphics in the periphery as displaying screen-fixed (Häuslschmid et al., 2015) and world-fixed (H. Kim et al., 2016) graphics in peripheral vision has shown promising results. Virtual cars like WA1 and WA2 require central AR HUD graphics which may interfere with visual demands of driving. World-relative graphics may be difficult for people to quickly understand and the addition of animation to graphics may further increase the temptation to look at a HUD for longer periods of time. Based on these results, it is likely that HUDs with larger fields of view and increasingly complex graphics will demand more visual attention. World-relative AR HUD graphics may offer much promise to the driving domain, they are not necessarily ideal for every scenario and concepts must be carefully tested, particularly those requiring space in the central field of view.

5.2. Driving Behaviors

HUD graphic type resulted in no differences in mean lane position, standard deviation of vehicle speed, standard deviation of lane position, or peak deceleration as participants approached a turn, which supports previous findings regarding driving behavior when using a virtual car and screen-fixed arrow for navigation (Topliss et al., 2018). Because graphic type had little impact on participants' driving behaviors in this study, HUD graphic type may not always influence driver behaviors. In this study, participants may have leveraged peripheral vision while using the HUD, making driving behaviors more consistent across different graphic types. Driving behaviors alone may not be sensitive enough to capture visual glance degradation over short durations or in this type of driving environment. Yet it is noteworthy that the presence of traffic and turn direction did change behaviors. Cross-traffic likely increased the complexity of the driving task as participants had to respond to traffic on the road rather than simply maintain lateral and longitudinal control and left turns are more demanding for US drivers than right turns (Fu et al., 2011). Therefore, these results are not surprising.

Taken in the extreme, results from this study could suggest that graphic spatial location and motion does not impact driving behaviors – a proposition that is intuitively hard to believe. While this overly simplistic view gives us more freedom as we design new graphics, there may be more nuance to this issue. We would expect to see more variation in lateral (e.g., lane position) and longitudinal (e.g., speed) vehicle control in more demanding conditions or, in this case, AR graphics (Horrey & Wickens, 2004a). Because participants reported differences in workload but we found no differences in vehicle control, a larger sample size or longer exposure time to graphics may have been required to capture these differences. In this study, we represented one type of information (navigation instructions) using four different graphic types with various combinations of screen- and world-relative, and fixed and animated graphics. Other information (e.g., hazard cues) may have a different impact on driving behaviors. We also analyzed driving data across 492 feet of travel as participants approached a turn. As participants make the turn and after completion of the turn, AR HUD graphic types may influence other driving behavioral changes.

5.3. Workload and Preferences

There were significant differences in reported demand (NASA TLX) and participants' preferred graphic type, unlike previous research (Bauerfeind et al., 2021; Topliss et al., 2018). Participants reported the lowest mental demand, physical demand, temporal demand, effort, frustration, and overall workload when using the screen-fixed graphic. Participants also reported better performance when using the screen-fixed graphic as compared to other graphic types. In contrast, WA2 was the lowest-scored graphic in terms of mental demand, physical demand, effort, frustration, performance, and overall workload. WA1 scored lowest for temporal demand. In addition, 72% of participants ranked the screen-fixed graphic as their *most* preferred display while 64% ranked WA2 as their *least* preferred display, showing strong preference for the screen-fixed graphic. Our results build upon previous work which has shown potential value of world-registered graphics by highlighting the importance of careful interface design: augmented reality alone does not inherently create a better experience for drivers. In fact, our results show that even for spatial location tasks, which are widely heralded as an ideal use case for world-registered AR graphics due to the need to integrate digital navigation instructions into the real world (e.g., Bauerfeind et al., 2021), integrating graphics alone does not improve performance. Graphics *integrated* into the world (rather than simply localized), must be further researched to fully understand the impact on end-users.

5.4. Limitations & Future Work

This study included some limitations due to the experimental design and technical challenges. Due to the significant technical challenge of integrating real-time AR graphics that respond to user inputs in a dynamic environment, we were only able to develop one route. Therefore, participants likely learned the route due to previous exposure, as evidenced by learning effects in the graphic order. We counterbalanced the order to mitigate the impact of learning on overall results but future studies should use novel routes for navigation studies to ensure that learning cannot occur. In addition to route knowledge, it is highly likely that all participants had previously navigated with graphics similar to the screen-fixed arrow which may have impacted their preferences or glance behaviors. Because this navigation method is widely used, future studies could train participants how to navigate with each of the different displays in order to mitigate novelty effects.

We used a single HUD for the entirety of this work, and the differing color and image quality across HUD hardware may impact drivers as well because it still could not perfectly match brightness and hue to make it appear as if part of the simulated urban environment. Participant strategies may have impacted results, as participants clearly learned over time. However, we accounted for this in our analysis and still found significant differences in glance behavior due to display. A significant number of participants that dropped out due to simulator sickness, which may mean our population was biased towards those that could tolerate turns in virtual reality and are less susceptible to motion sickness. Ideally, these studies should include a variety of populations, especially accounting for different genders and age ranges.

Because of the large, and likely infinite, number of possibilities, we did not fully explore all possible graphic types or driving tasks. We also only included world-registered and *integrated* graphics, without including comparable *localized* graphics. Because the screen-fixed graphic resulted in lowest mental demand and highest hazard scanning, and there were no differences in driving performance, world-registered and localized graphics may be a useful graphic type, and should be explored further. It is likely not possible to explore every conceivable task and all methods of conveying pertinent information about the tasks, but broader coverage will surely be useful in building knowledge further. While we designed this study such that there were no hazards in participants' driving lane, this should be addressed with future work. The occlusion of potential road hazards by HUD graphics could result in drivers missing pertinent hazards and wrecking the vehicle.

6. Conclusion

We examined the impact of AR graphic point of reference and motion on drivers, finding that the methods in which AR HUDs present information can impact driver scanning behaviors and preferences. More work is required to understand the impact of AR HUD use on drivers' abilities to identify and react to hazards. Current automotive HUDs use simple and screen-fixed graphics, but future displays may use more complex graphics which may impact drivers' glance behaviors and change how they scan the environment for roadway hazards. Thus, driving research needs to explore the impact associated with perfectly conformal images. It is possible that an image that matches depth and illumination of real-world objects may be processed simultaneously with the world. However, such a display does not currently exist and until such a time that this technology is available, this research provides some evidence that we need to find ways of analyzing AR HUDs in the context of real driving situations. Ultimately, this work shows that while AR HUDs provide promise for future in-vehicle displays, further research is needed to understand how display location impacts driver behavior and to determine specific graphical guidelines that minimize visual demand needed to process spatially located graphics.

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