Guiding Driver Responses During Manual Takeovers from Automated Vehicles

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Abstract

The number of automated features in surface vehicles is increasing as new vehicles are released each year. Some features allow drivers to temporarily take their attention off the road to engage in other tasks. However, sometimes it is important for drivers to immediately take control of the vehicle. To take control safely, drivers must understand what is required of them and have the situation awareness (SA) to understand important changes or factors within the environment around them. To achieve this, drivers may be presented with necessary takeover information using a head-up display (HUD), which keeps the driver's eyes on the road. This study investigated the impact of novel HUDs on driver SA during takeover on highways. Data collection included empirical data for takeover performance metrics, self-reported SA, and participant preferences. To investigate differences between conditions, statistical analyses utilized repeated measure analyses of variance (ANOVAs). The results indicated that HUDs can increase aspects of takeover performance on highways, with participants demonstrating lower response times and higher time-to-collision metrics. There was no significant impact of HUDs on driver SA. Results of this work identified potential use cases and design criteria for new designs of novel HUDs to deliver important information during takeover.

Acknowledgements

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Introduction

Various advanced vehicle technologies currently exist that, when activated simultaneously, will control both the lateral and longitudinal position of the vehicle (i.e., lane centering assist and adaptive cruise control, respectively). Referred to as Level 2 (L2) partial driving automation by SAE International [1], these driving automation systems are designed to carry out part of the dynamic driving task (DDT) on a sustained basis within a particular operational design domain (ODD); however, these systems also require drivers to remain vigilant in a supervisory role and be ready to take control of the vehicle if needed [1]. L2 systems are intended to support, not replace, the driver. Advancement of research and technology seeks to achieve higher levels of automation (i.e., Level 3 to 5), which will increasingly remove drivers from the DDT.

Level 3 (L3) automation and higher specifically refers to an Automated Driving System (ADS) that performs the complete DDT but still requires drivers to be fallback-ready in cases where the DDT exceeds the system's ODD. The ADS performs latitudinal and longitudinal control simultaneously, as well as the object and event detection and response task. However, some systems only perform under specific conditions; thus, the human driver is needed for instances when conditions exceed operational capabilities [2]. For example, an L3 ADS may require clearly visible lane lines for the lateral control of the vehicle to function safely and effectively. If the lane lines are obscured for brief periods of time, such as within a work zone, the ADS feature can compensate through other methods (e.g., using a digital map, following a lead vehicle) until the lane lines are visible again. However, if the lane lines are obscured for too long, the ADS feature will request the fallback-ready user to intervene and disengage the system. In instances of ADS disengagement, drivers are responsible for returning the vehicle to a minimal risk condition. Disengagement can come from systems in the form of handover to fallback-ready users when limits of the ODD are about to surpass or have surpassed functional limits with no warning given [1].

In addition to vehicle-initiated disengagements, drivers can also disengage ADS quickly and easily and immediately take over control of the vehicle. Safety in emergency time-dependent events is important in L3 automation because drivers may not be attentive to their surroundings due to engagement in non-driving related tasks. When appropriate, timely handover requests should be issued, but not all situations allow for this, and some may require more immediate driver takeover. It is important to note the distinction between the terms *handover* and *takeover*, as they are often used interchangeably when explaining the transfer of control from automated systems to drivers. However, transfer of control is a multiple-step process involving both handover and takeover. *Handover* is defined as the overall period when the automated vehicle is transitioning control over to the driver, while the response of the driver when regaining control is a *takeover* [3].

Human Machine Interface

The human machine interface (HMI) is critical for communication between the ADS and the driver, thereby creating an effective and acceptable system for human use. Systems must be able to convey a message to the user, and the user must detect the message in a timely manner and interpret it correctly. Displays often use combinations of multiple modalities, such as auditory, visual, and haptic displays, to increase the odds of capturing the driver's attention and to improve ADS communication with drivers [4, 5, 6]. Messages and alerts are designed for different purposes and convey different information, which determines how these messages are communicated to the driver. Thus, an effective HMI is an important component in the presentation of takeover requests (TORs). TORs may be presented for a variety of reasons, but these requests are often time constrained and require quick and efficient driver responses. Failure to respond quickly and correctly can lead to negative consequences.

State-of-the-art HMI options for the presentation of TORs involve novel technologies, such as an augmented reality (AR) head-up display (HUD). As shown in Figure 1, visual information presented via an HUD can be anchored in two ways. Screen-relative graphics place an image in the view of the driver oriented to the visual plane of the HUD, which gives the user information while being anchored to the display [7]. The vehicle speed and navigation directions shown in Figure 1 are an example of screen-relative graphics. World-relative graphics, such as the yellow marker shown in Figure 1 highlighting the vehicle ahead, are anchored to the world itself and can utilize orienting images from the surrounding environment to indicate lane safety [8]. AR HUDs can overlay colored symbols in the real world to direct drivers to either brake or change lanes, giving more constant braking and steering actions [9, 10]. The use of world-relative graphics may also help quickly guide user attention to needed features if they are mapped correctly to the real world [11]. This gives drivers the ability to understand and then carry out actions to avoid collisions or roadway obstructions. Visual information can also be presented via the more commonly available head-down display (HDD), with displays located on the instrument cluster and the center console. In addition to visual information, auditory cues can be presented as either beeps/pulsed tones or voice messages (either real or computer-simulated speech). Information conveyed by tones or beeps is obviously very limited and will typically cue drivers to a change in automation status or alert the driver to an event requiring their attention. Voice commands can be used to present more complex information, such as alerting the driver to take control of the vehicle (e.g., "take over now").

Figure 1. Photo. HMI design using world-relative HUD graphics (i.e., yellow marker that follows the vehicle ahead) and screen-relative HUD graphics (i.e., vehicle speed and navigation directions) [8].

The challenge in creating an effective HMI is that increased levels of automation are associated with an increase in secondary task engagement and eyes-off-road time [12, 13, 14], which subsequently have a detrimental impact on situation awareness (SA) [15, 16]. Currently available HMIs typically use visual and/or auditory cues to direct the driver's attention back to vehicle control without providing further information about the dynamic driving situation, which is critical for the driver's SA and resulting response selection. Thus, TORs that are presented when the driver is engaged in non-driving (i.e., secondary) tasks may lead to long response times and inappropriate responses to imminent potential conflicts.

Objectives

The overall objective of this research was to explore multimodal HMI approaches to improve driver SA and help shape the driver's initial response in challenging takeover situations. This was achieved by:

- Developing new and novel multimodal HMIs for handover situations, and
- Evaluating the effects of various modalities of HMIs on handover of automated vehicles by assessing driver SA, takeover performance, and acceptance of vehicle automation.

Specifically, this project addressed the following research questions:

1. In what ways is driver SA affected differently by TORs delivered via HUD using screen-relative graphics and world-relative graphics on a HUD when compared to screen-relative graphics on HDDs?
2. How does driver performance during takeover differ between screen-relative HUDs, world-relative HUDs, and HDDs?
3. Do drivers report greater preference levels for HUD presentation styles than for the HDD presentation style?

Method

Participants

A total of 21 participants (12 male and 9 female) were recruited using the Virginia Tech Transportation Institute (VTTI) participant database. The VTTI recruitment team identified potential participants in the database (i.e., based on pre-determined inclusion criteria), then contacted them via email to share recruitment materials. Participants were required to be between 21 and 50 years old, have a valid U.S. driver's license with at least 2 years of driving experience, and not wear corrective eyeglasses (contact lenses were acceptable). The participants were compensated $60 for full participation. All participants were from the New River Valley region of Virginia. The average age of participants was 33.5 years old (SD = 6.5 years, R = 22-44 years old), and average self-reported driving experience was 16.62 years (SD = 7.2 years, R = 4-28 years). The study methodology and materials were approved by the Virginia Tech Institutional Review Board (IRB).

Virtual Reality Driving Simulator

A virtual reality (VR) driving simulator was developed in the Unity platform, and the driving experience was simulated using an HTC VIVE headset and Logitech G920 force-feedback steering assembly. To give a more real-world feel, drivers were seated in an electronically adjustable proprietary vehicle seat provided by a major vehicle manufacturer. The simulator also included floor-mounted pedal assembly, a mounted steering wheel that provided haptic cues, and mounted speakers for auditory cues (Figure 2). Inside the virtual environment, the user's perspective included a first-person view sitting in the driver's seat inside of a car. The virtual car simulated attributes of a real vehicle, and the virtual steering wheel and pedals were animated in response to participants' manipulation of the physical steering wheel and pedals. The center console was covered by a virtual display that was used for displaying the secondary task and the TOR alerts. The simulated driving scenario featured a long straight road and included other cars and obstacles. Participants experienced a variety of takeover scenarios cued by a combination of auditory, visual, and haptic alerts. A series of questions was asked after each trial to assess participants' SA.

Figure 2. Photo. Picture of driving simulator apparatus with labeled takeover modality features.

The vehicle in this study simulated an L3 driving automated system, in accordance with SAE J3016 [1]. When enabled, the automated driving system operated the vehicle's longitudinal and lateral movements, meaning the system kept the vehicle centered in its own lane and a set distance from other vehicles ahead, in the same lane. However, unlike the J3016 definition for L3 automation, participants needed to be ready to promptly reengage in the driving task when needed. In cases where the scenario exceeded the system's capabilities, the system issued a TOR, after which drivers were required to immediately regain vehicle operation by disabling the system using one of the controls (i.e., pressing and releasing one of the paddles behind the steering wheel, pressing the brake, pressing the accelerator, or turning the steering wheel).

Experimental Design

A 3x3x3 full factorial within-subjects design was used whereby participants experienced each HMI scenario once. This factorial design combined three auditory, visual, and haptic cues for each HMI (Table 1). Each participant experienced 27 test conditions and three scenarios where no obstacle was in the road, known as dummy conditions, for a total of 30 conditions per participant.

Table 1. Visual, Auditory, and Haptic Cues for Each HMI

Cues	Condition
Visual	Icon (HDD)
Visual	World-Relative (HUD)
Visual	Screen-Relative (HUD)
Haptic	Guiding
Haptic	Restricting
Haptic	Off
Auditory	Tone-> "Turn ____"
Auditory	Tone-> "Takeover Required"
Auditory	Tone

Procedure

To begin the study, participants were brought in and seated in the driving simulator. Consent was obtained as per IRB requirements, and participants were given basic instruction and study background. Next, participants were screened for visual acuity, color blindness, and hearing loss. Participants who had less than 20/40 vision or greater than 40-dB hearing loss were excluded from the study. Visual and auditory acuity levels were in accordance with the requirements to obtain and maintain an unrestricted driver's license. Colorblindness was not an exclusion criterion but was noted by researchers. Participants then filled out a survey to provide basic demographic information, driving characteristics, and their experience with advanced vehicle safety systems. Finally, participants completed the Simulator Sickness Questionnaire (SSQ) [17].

Next, participants were seated in the driving simulator where they were fitted with the VR headset, which was an HTC VIVE VR head-worn display (HWD) with a built-in HTC VIVE eye-tracker. Once the participant was comfortable, the seat position was adjusted for participant height to ensure accurate eye movement measurements were calibrated. Participants were then placed in the virtual world and given basic instruction on the manual driving functions of the driving simulator. They were given up to 5 minutes to acclimate to their surroundings and practice manually driving, stopping, and turning the vehicle. Once they were comfortable, they were asked to bring the vehicle to a stop in the center lane, after which they were instructed on the functions of the driving automation system. Once participants understood the capability of the system, they were instructed to engage the driving automation system by pulling on either the right or left paddle switch located behind the steering wheel. The same pulling action of the paddle switch also disengaged the system and returned the vehicle to manual driving. Participants were then instructed to drive for another 5 minutes to acclimate and become comfortable enabling and disabling the autonomous driving system. During this acclimation process, participants were instructed on how to complete the secondary task and given time to practice. After the acclimation process, participants brought the vehicle to a stop and removed the HWD to fill out the SSQ for the second time [17].

After participants completed the SSQ, and if they were comfortable proceeding, participants put the HWD back on and were placed back in the virtual vehicle, where the experimenter gave basic instructions about the different alerts they may experience. While the virtual vehicle was stationary and before the participant began the main study drives, the experimenter triggered each TOR manually so participants would experience each TOR alert individually. First, the three visual TORs were individually triggered, followed by each auditory and haptic TOR. Once the TOR introduction was over, participants began the main study drives.

To begin, participants were instructed that their main task was to ride in the automated vehicle unless they felt other action was required. They were asked to keep both hands on the steering wheel but were not told to maintain any other involvement in the driving task. Participants enabled the automation, and the driving automation system brought the vehicle up to 55 mph and maintained speed and lane position. Participants experienced a TOR between 30 to 90 seconds into each of the 30 trials. After they reacted to the alert, the HWD screen immediately went black to signify the end of the trial, and the participants were presented with the SA global assessment technique (SAGAT) to assess their SA. When participants were ready, they proceeded to the next drive. Every 10th trial, participants completed the SSQ to measure signs of simulator sickness. Breaks were allowed after any trial but were required after the 10th and 20th trials. After the final trial, participants removed the HWD and completed the TOR preference survey, gave overall impressions of aspects of the system, and completed an agreement scale. Participant sessions lasted between 60 and 90 minutes.

Secondary Search Task

During each trial, participants completed a secondary search task that involved verbally telling the experimenter the number of occurrences of the letter “a” on a visual display located on the center console (i.e., where most vehicles have radio and heating, ventilation, and air-conditioning controls). This location required participants to take their eyes off the forward roadway, thereby serving as a visual distraction. The letter “a” could be presented in upper case or lower case and typically occurred zero to six times per cycle. The experimenter manually cycled the screen after each verbal response from the participant, with the secondary task carried out until the TOR from the system signaling the completion of each trial. Figure 3 shows the design and location of the secondary search task in the simulated driving environment.

Figure 3. Screen shot. User perspective of the secondary search task.

The TOR presented on the center console was triggered by time-to-collision (TTC) with an obstacle in front of the vehicle, such as a broken-down vehicle or object. This TOR icon (Figure 4) indicated to the participant that they needed to retake control of the vehicle immediately and respond to the imminent collision.

Figure 4. Screen shot (left) and graphic (right). TOR graphic presented in the center console display.

Driving Scenarios

For each trial, participants experienced one of three driving scenarios with variations in actor vehicle locations to the left or right of the participant's vehicle, labeled accordingly in Figure 5 with "L" or "R." These scenarios utilized multiple vehicles around the participant's vehicle. Driving scenarios and obstacles were counterbalanced to ensure each participant received each combination of scenario and obstacle. The actor vehicle varied in the three scenarios, with either a black or red vehicle on the left or right that accelerated after a given time, or a vehicle in front of the host vehicle that changed into the right or left lane shortly before approaching an obstacle. A second vehicle was always following directly behind the host vehicle in the center lane, and a third vehicle was always in the right or left blind spot, depending on the scenario. Additionally, three different obstacles were used to emulate possible obstructions a vehicle may experience on a real road. The obstacles were always in the center lane and consisted of either a series of construction cones, a large brown box, or a stopped vehicle. In the control scenarios, the host vehicle did not have a physical obstruction in front of it, but lane markings disappeared, which simulated a situation where a system may no longer be able to function, requiring driver takeover.

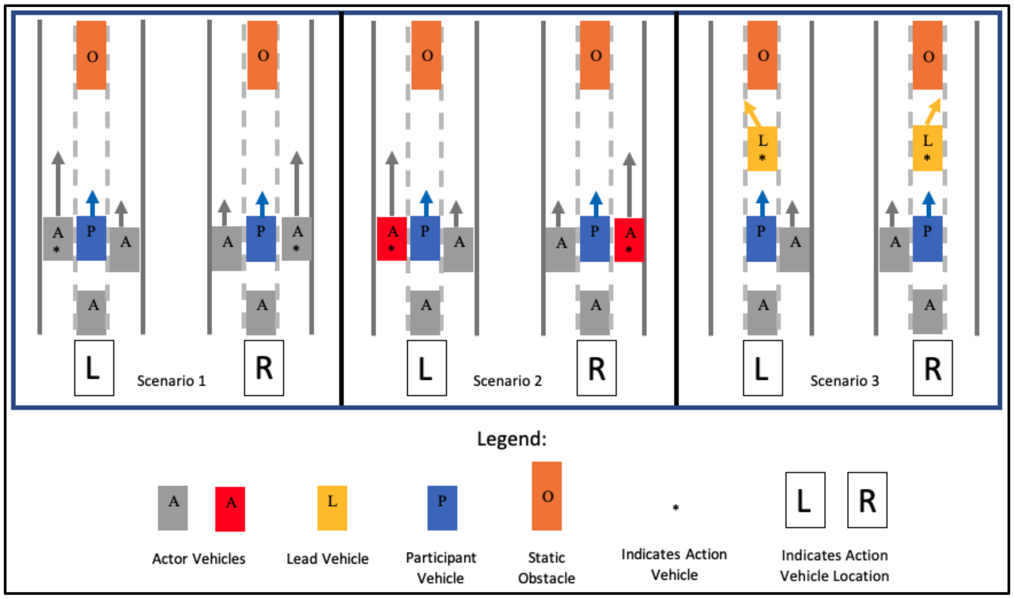

Figure 5. Diagram. Graphic of Scenarios 1, 2, and 3 indicating actor vehicles, location, and maneuvers.

HMIs

Visual

Several different visual displays were used in the simulated driving scenario. The first display was an HDD comprising a simple icon located between the speedometer and tachometer in the gauge cluster. This display utilized a colored letter icon of "A." When in manual mode, a black-and-white A was displayed, changing to a green-and-white A when automation was enabled, and a red-and-black A when automation was disabled (Figure 6).

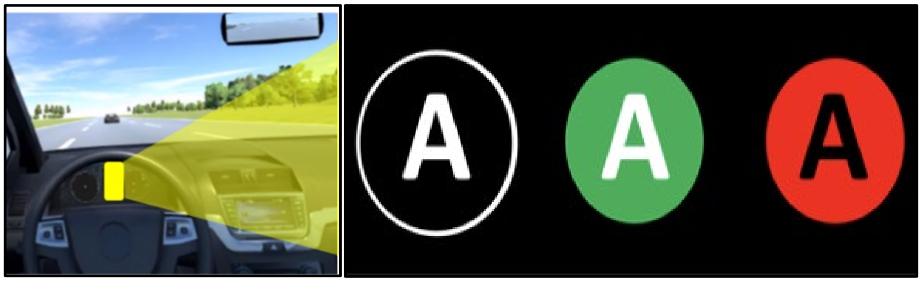

Figure 6. Screen shot (left) and graphic (right). Automation indicators located in the gauge cluster of the vehicle.

Participants also experienced two different HUD graphic conditions during the driving scenarios:

1. A world-relative graphic display that overlaid colored lanes over the existing lanes to show lane availability, with green symbolizing the lane was available and safe and red showing the opposite (Figure 7).
2. A screen- relative graphic display showing a bird's-eye view of the vehicle and the surrounding lane availability (Figure 8).

Figure 7. Screen shot. An example of the world-relative HUD graphic scenario.

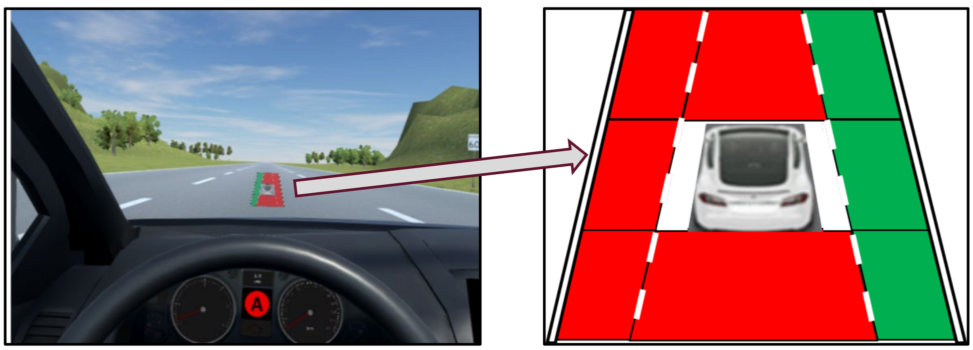

Figure 8. Screen shot (left) and inset (right). An example of the screen-relative HUD graphic displayed (left image) and a close-up of the screen-relative HUD graphic (right image).

Auditory

A total of three auditory conditions were used in this study. A sinusoidal tone was used to emulate many current auditory alerts used in vehicles. Two different voice commands were added after the sinusoidal tone to give drivers further information. These two voice commands consisted of a male voice saying, “Takeover Required,” “Turn Left,” or “Turn Right” (i.e., depending on the scenario).

Haptic

A haptic steering wheel was also implemented with two types of steering wheel responses (Figure 9). In some scenarios, participants experienced a nudge in the steering wheel that was meant to direct them to steer into the direction the nudge was given (i.e., a guiding, or feedforward, control input). In other situations, participants experienced a pulsed resistance in the steering wheel (i.e., a restricting, or feedback, control input). This resistance was only felt when drivers made incorrect steering responses, such as when attempting to turn into a lane with a vehicle in their blind spot. Some scenarios did not utilize haptic steering inputs as a control condition.

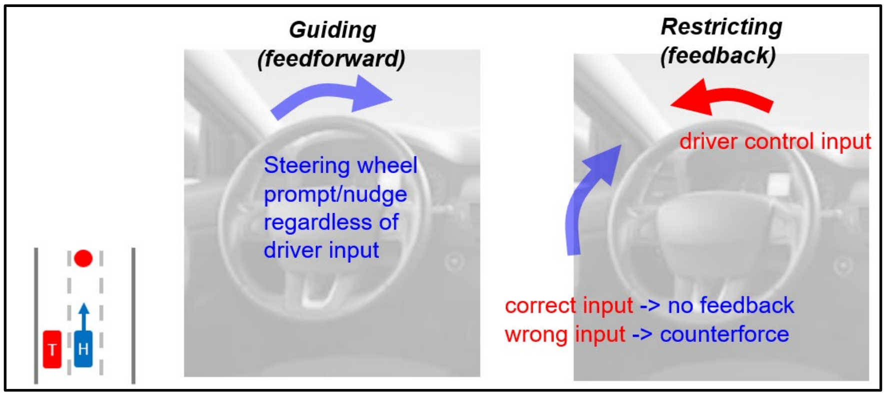

Figure 9. Diagram and images. Graphic depicting haptic steering wheel providing guiding or restricting control input.

Results

Data Reduction and Analysis

The simulator logged all data from each trial. To identify reaction times, movement of the steering wheel and brake pedal were checked to see if they had passed a certain threshold after the alert had occurred. Importantly, the brake pedal needed to be pressed to exceed the threshold used to deactivate the driving automation system, while the steering wheel position had to be moved for a large enough delta over a five-frame window. The driver was determined to have been involved in a crash if they moved to the incorrect lane or stayed in their current lane. Incorrect lane crash would be due to hitting a car in their blind spot, while staying in the current lane implies either they ran into the obstacle or were rear-ended by the car traveling behind. The minimum distance to the obstacle was set as the point where the participant either crashed or changed lanes. The minimum TTC was calculated by first smoothing the TTC live estimate data with a moving average over a window of three frames, then checking for the minimum prior to braking, lane change, or simulation end.

SA data were coded for premature lane changes or other problems that occurred during the duration of the study. Each SA variable was transformed into the percentage correct in terms of each variable coded, and those scores were compared to the ground truth, such as percentage of correct object identification and percentage identification of TOR modalities, shown in Table 2.

Table 2. SA Score Calculation Variables

SA Score Variable	Explanation
Percent Lane Score	Percentage of participants that perceived their position in the correct lane
Percent Location Score	Percentage of participants that correctly identified objects around them
Percent TOR Score	Percentage of participants that correctly identified TORs used in the drive
Percent Meaning	Percentage of participants that correctly understood the alert meaning
Percent Response	Percentage of which participants correctly identified future events
Overall SA	Average from variable collected.

Participants indicated their TOR preferences using both a ranking scale and open-ended responses. Participants ranked their preference for each TOR on a scale from 0-10, lowest to highest according to how much they liked the TOR and if they would like to see it included as a future vehicle feature. To assist participants' recollection of TORs, visual graphics of each TOR and a written explanation were provided. Participants also provided open-ended responses in which they were able to provide greater context for why they preferred certain TORs and contribute input for future TOR designs.

Assumption Testing

To begin data analysis, the data were tested for normality with a Shapiro-Wilk normality test. Data that departed from normality were logarithmically transformed, and repeated measures analyses of variance (ANOVAs) were conducted. Logarithmic data were back-transformed to present the findings to their original units for reporting results. All significant results from the repeated measures ANOVAs were further analyzed using appropriate post hoc tests accounting for the repeated measures design with multiple comparisons. The statistical software SPSS (version 27.0.1.0) was used to analyze all data. Results of the repeated measures ANOVAs indicated that the data did not violate Mauchly's test of sphericity, so results reflect assumptions of sphericity. Due to missing data, two participants' data were removed from the ANOVAs.

SA

To identify main effects, a repeated measures ANOVA was conducted to investigate the effects of the combination of visual graphics and auditory displays on a participant's overall SA. Results of the test did not indicate main or interaction effects between visual graphic conditions ($F(2,17) = 2.277$, $p = .133$), auditory cue conditions ($F(2,17) = .142$, $p = .869$), or interactions between visual and auditory conditions ($F(4,15) = .251$, $p = .905$; Figure 10). Mean scores for each graphic and auditory condition revealed that participants in the HDD graphic condition with tone only indicated a mean overall SA score of 79.61% ($SD = 11.39$), participants in the HDD graphic condition with tone and "Takeover Required" cue indicated a mean average of 78.99% ($SD = 11.39$), and participants in the HDD graphic condition with tone and directional cue indicated 77.59% ($SD = 18.26$).

Mean scores for the world-relative HUD graphic and auditory conditions revealed that participants in the world-relative HUD graphic condition with tone only indicated a mean overall SA score of 81.23% ($SD = 15.04$), participants in the world-relative HUD graphic condition with tone and "Takeover Required" cue indicated a mean average of 82.59% ($SD = 11.65$), and participants in the world-relative HUD graphic condition with tone and directional cue indicated 84.91% ($SD = 9.35$).

Mean scores for the screen-relative HUD graphic and auditory conditions revealed that participants in the screen-relative HUD graphic condition with tone only indicated a mean overall SA score of 80.13% ($SD = 13.76$), participants in the screen-relative HUD graphic condition with tone and directional cue indicated 82.85% ($SD = 11.23$), and participants in the screen-relative HUD graphic condition with tone and "Takeover Required" cue indicated a mean average of 80.75% (*SD* = 11.04).

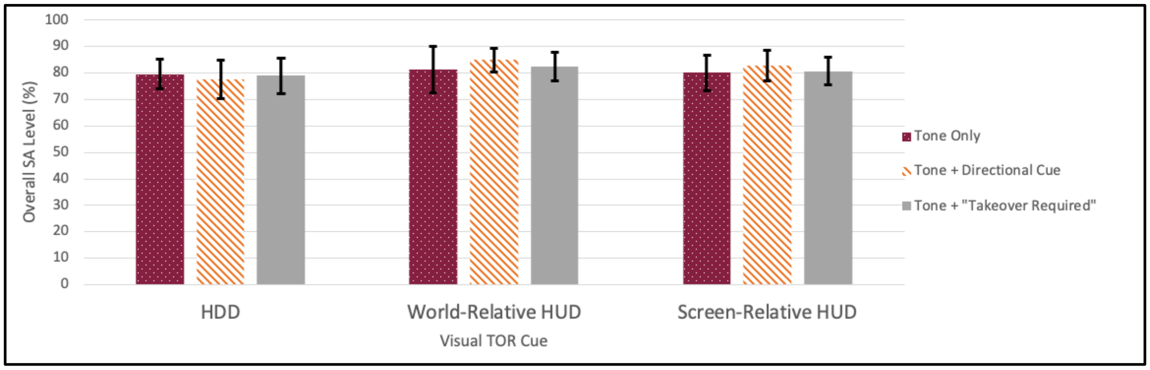

Figure 10. Graph. Participants' average overall SA score per visual and auditory display. Error bars indicate 95% confidence intervals.

Initial Response Time

The effects of visual graphic presentation styles and auditory cues on a participant's initial response time were investigated using a repeated measures ANOVA. Results indicated significant differences between visual modalities ($F(2,17) = 14.029$, $p < .001$); however, there was no significant difference (Figure 11) between auditory cue conditions ($F(2,17) = .252$, $p = .780$) or interactions between visual and auditory conditions ($F(4,15) = 2.560$, $p = .082$). A pairwise post hoc test with Bonferroni adjustment for multiple comparisons was conducted with the visual graphic presentation style, with results indicating significant differences between HDD ($M = 2.025$, $SD = .162$) and world-relative HUD ($M = 1.601$, $SD = .134$) graphic conditions, $p < .001$, and HDD ($M = 2.025$, $SD = .162$) and screen-relative HUD ($M = 1.739$, $SD = .129$) graphic conditions, $p < .05$. Results indicated that participants responded more quickly in the world-relative and screen-relative HUD visual graphic presentation styles when compared to the HDD visual graphic presentation style. No significant difference was found between the world-relative HUD ($M = 1.601$, $SD = .134$) and screen-relative HUD ($M = 1.739$, $SD = .129$) graphic conditions.

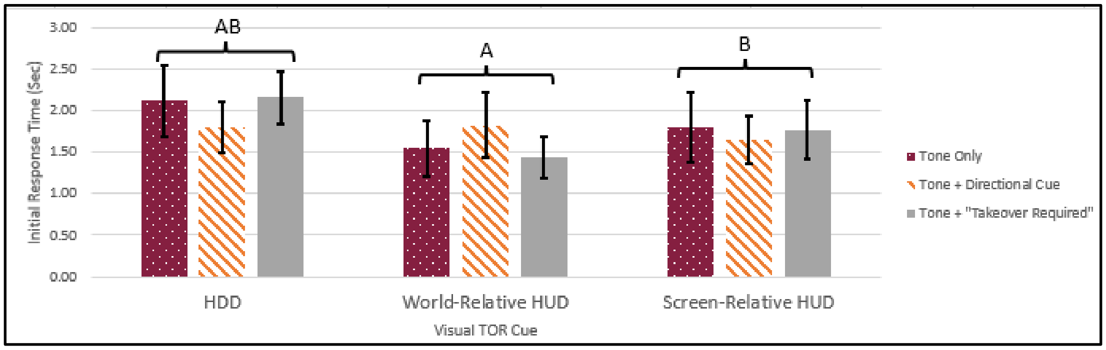

Figure 11. Graph. Mean initial response times by visual and auditory condition. Error bars indicate 95% confidence intervals. Letters (A/B) are used to label significantly different groups reflecting results of post hoc pairwise comparisons with Bonferroni adjustment for multiple comparisons.

TTC

TTC was analyzed to investigate the effects of visual graphic presentation styles and auditory cues. Results of a repeated measures ANOVA indicated significant differences between visual graphic conditions ($F(2,17) = 11.601$, $p < .001$). Results did not indicate significant differences between auditory cue conditions ($F(2,17) = .047$, $p = .954$) or an interaction between visual graphic and auditory cue conditions ($F(4,15) = 1.938$, $p = .156$). A pairwise post hoc test revealed significant differences in minimum TTC between the HDD graphic ($M = 2.061$, $SD = .140$) and world-relative HUD graphic ($M = 2.512$, $SD = .139$) conditions, $p < .001$. Results indicated significant differences between the HDD graphic ($M = 2.061$, $SD = .140$) and screen-relative HUD graphic ($M = 2.332$, $SD = .140$) conditions, $p = .05$. No significant differences were identified between the world-relative HUD graphic ($M = 2.512$, $SD = .139$) and screen-relative HUD graphic ($M = 2.332$, $SD = .140$) conditions. Results (Figure 12) indicated that participants in the world-relative HUD graphic condition had an increased TTC, meaning participants in the world-relative graphic HUD condition completed the correct action to avoid the obstacle with an increased time distance between their vehicle and the obstacle in front of them when compared to the HDD graphic condition.

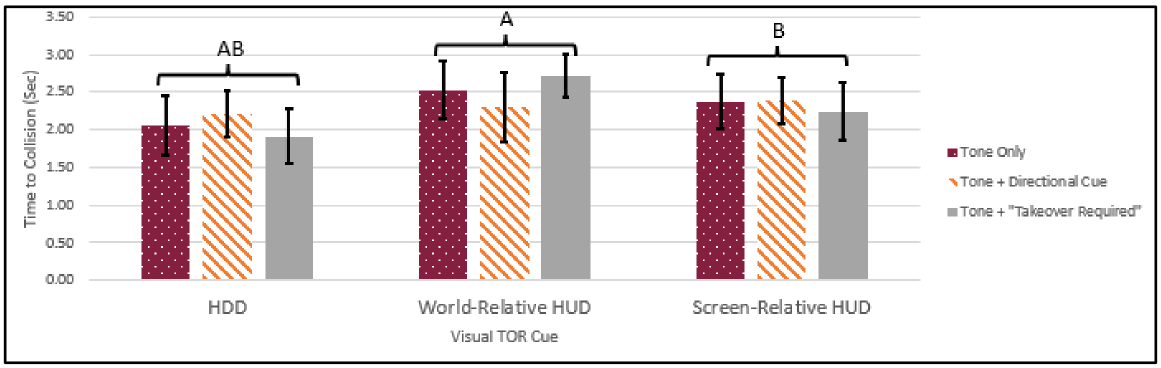

Figure 12. Graph. Average of calculated TTC. Error bars indicate 95% confidence intervals. Letters (A/B) are used to label significantly different groups reflecting results of post hoc pairwise comparisons with Bonferroni adjustment for multiple comparisons.

Reaction Accuracy

A binomial logistic regression was conducted to investigate the effects of visual graphics and auditory cues on reaction accuracy, which was quantified by a binary variable (i.e., correct or incorrect). Results indicated that visual graphics, auditory cues, or an interaction of auditory and visual cues did not contribute to the model (Table 3).

Table 3. Binomial Logistic Regression Results

Cue Type	Exp(B)	95% Confidence Interval for Exp(B): Lower	95% Confident Interval for Exp(B): Upper
Visual	-	-	-
Visual (1)	8	0.869	73.683
Visual (2)	7.6	0.823	70.158
Auditory	-	-	-
Auditory (1)	1.12	0.278	4.508
Auditory (2)	0.65	0.178	2.369
Auditory*Visual	-	-	-
Auditory (1) by Visual (1)	0.893	0.038	21.113
Auditory (1) by Visual (2)	0.446	0.026	7.695
Auditory (2) by Visual (1)	1.538	0.068	34.867
Auditory (2) by Visual (2)	0.344	0.025	4.761

TOR Preference

Results of a Friedman test indicated a significant difference in participant preferences of the visual graphic conditions, χ^2 (2, n = 21) = 23.761, $p < .001$. A Wilcoxon signed-rank post hoc test revealed significant differences between visual graphic conditions (Figure 13). A significant difference in visual graphic conditions indicated that participants preferred the screen-relative HUD graphic (Md = 7, n = 21) over the HDD graphic (Md = 4, n = 21), z = -3.255, p = .001. The world-relative HUD graphic condition (Md = 10, n = 21) was preferred by participants over the HDD graphic (Md = 4, n = 21), z = -3.493, $p < .001$, while participants preferred the world-relative HUD graphic (Md = 10, n = 21) over the screen-relative HUD graphic (Md = 7, n = 21), z = -3.023, p = .003.

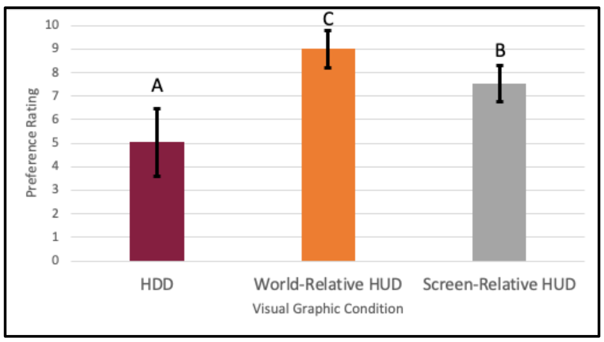

Figure 13. Graph. Average of participant preferences of visual graphic condition. Error bars indicate 95% confidence intervals. Letters (A/B/C) are used to label significantly different groups reflecting results of post hoc pairwise comparisons with Bonferroni adjustment for multiple comparisons.

To evaluate participant preference of auditory cues, a Friedman test was conducted to investigate preference differences between auditory conditions. Results indicated a significant difference between participant preference of auditory cue conditions, $\chi^2 = (2, n = 21) = 15.079$, $p < .001$ (Figure 14). Results indicated significant differences between tone only cues ($Md = 7$, $n = 21$) and tone with directional cues ($Md = 9$, $n = 21$), $z = -2.650$, $p = .008$. Participants also preferred the tone with directional cue ($Md = 9$, $n = 21$) condition over the tone with “Takeover Required” ($Md = 7$, $n = 21$), $z = -2.979$, $p = .003$. Results did not reveal significant differences in preferences between tone only ($Md = 7$, $n = 21$) and tone with “Takeover Required” ($Md = 7$, $n = 21$), $z = -.657$, $p = .511$.

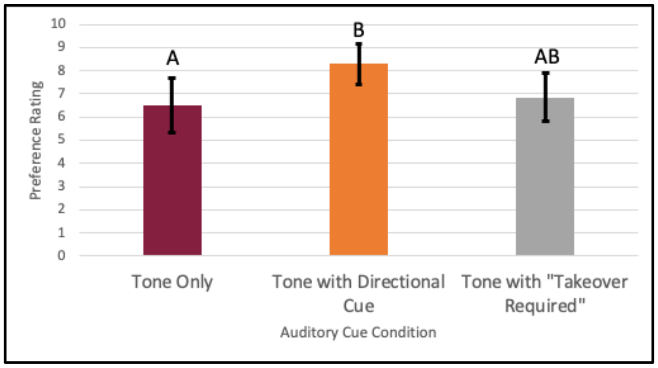

Figure 14. Graph. Average participant preferences of auditory cue condition. Error bars indicate 95% confidence intervals. Letters (A/B) are used to label significantly different groups reflecting results of post hoc pairwise comparisons with Bonferroni adjustment for multiple comparisons.

Discussion

SA

Participants’ overall SA scores did not significantly vary between visual and auditory cue conditions, and participants overall displayed a relatively high level of SA (as reflected in mean SA scores). Specifically, SA data did not reflect that participants indicated increased SA levels in the HUD graphic conditions compared to the HDD graphic condition. Mean scores likely reflect increased average scores such that HDD graphics had a mean score of 78.73%, world-relative HUD graphics had a mean of 82.91%, and screen-relative HUD graphics had a mean of 81.24%, all with standard deviations above 10%.

High mean SA scores could be due to an increase of factors, such as participants’ understanding of proper locations of obstacles or other vehicles around them. The amount of driving scenarios and the commonalities of vehicle locations may have had an effect on drivers’ understanding of the obstacles around them and understanding that those obstacles existed in every drive. Participants also may have correctly perceived the presence of visual and auditory alerts, as those alerts were intended to be salient and to alert drivers to an action. Both visual and auditory alerts also had different levels of meaning, whether they presented implicit or explicit cues to participants (e.g., giving them visual or verbal direction of the action to take). Giving varying levels of information could have not only helped participants understand the meaning of the alerts, but also helped them anticipate future events and actions. Participants also may have maintained an awareness of other vehicles around them by assessing their surroundings before enabling automation. Actor vehicle starting positions did not vary by drive, and an actor vehicle was always present behind the participant's vehicle. We did note when participants looked around at their surroundings before enabling the vehicle's driving automation system, which we will analyze in the future to see if participants looking at their surroundings before enabling the system affected their SA.

Participants' SA scores reflected the highest percentages in both HUD graphic conditions, which helps to support the use of HUD graphics in takeover. Further analysis of eye-tracking data may indicate areas of participant gaze fixations and gaze patterns during takeover. Gaining understanding and comparing objects of interest and gaze patterns between HUD graphic conditions and the HDD condition may indicate differences in gaze path, what participants focused on, and for how long they focused on that area after the TOR was issued. Understanding the timing and sequence helps us understand if a participant's gaze reflects appropriate visual reactions to the alert and if a participant's gaze locations vary between HUD and HDD graphic conditions (e.g., did the participant's gaze move towards the direction indicated in the alert or did their gaze move to the obstacle in the road).

Though results did not indicate differences in participant SA between graphic conditions, this study serves as a proof of concept for future HMI developments to increase driver SA during takeover. We created world-relative and screen-relative HUD graphics that indicated the presence of other vehicles on the roadway and utilized TORs to guide drivers in safe responses to situations where evasive maneuvers were required. As systems progress, drivers will inevitably encounter such situations in which they are required to make an evasive maneuver during takeover, when they are required to quickly perceive the current situation and react safely. Drivers benefit from projections of vehicle locations and safe lanes around them to increase their SA during takeover.

Takeover Performance

Participants' takeover performance, in terms of TTC and initial-response time, also indicated results favoring the use of HUD graphic conditions, with no calculated effects from auditory cues. Participants exhibited the highest TTC, improving takeover performance, in yielding significant differences between the HDD graphics and world-relative HUD graphics and the HDD graphics and screen-relative HUD graphics. Results align with our expectations, as participants were provided with more visual information presented directly in their line of sight. The information presented not only indicated the presence of other road actors, but also indicated safe areas to maneuver the vehicle, yielding increased TTC and improved takeover performance. We also allowed participants ample time to change lanes, with a time budget of 5 seconds from alert initiation to when they would strike the obstacle in their lane. This time budget may have allowed participants to quickly check their surroundings before changing lanes.

Analyses yielded similar findings for initial-response times. Specifically, world-relative HUD and screen-relative HUD graphic conditions were associated with the lowest response times compared to HDDs, with no significant difference in response times between HUD conditions or effects from auditory cues. This lends support to the improved takeover performance potential of AR HUD graphics, though these data have not yet been translated to takeover time. Future research may benefit from investigating both initial response time and time to takeover, as this would provide empirical data from the entire takeover process from alert initiation to participant response, to the participant having full control of the vehicle. We would expect to see similar results in terms of takeover time but would require further data analysis.

Participants did not indicate a significant difference in correct responses between visual or auditory conditions. Overall, participants completed the correct action on 84.4% of the drives, indicating that drivers consistently made correct actions to avoid collisions. Further analysis would benefit from categorizing incorrect actions into incorrect lane deviation or crash. Understanding what incorrect action was taken may help investigate if participants comprehended there was an actor vehicle behind them that struck them. Future studies may also benefit from decreasing the time budget, requiring quicker driver responses, which may be aided by HUD graphics.

Results of this study supported use cases of world-relative HUDs improving takeover performance. Improving takeover performance by reducing reaction time and increasing TTC is imperative for increasing safety of motorists on highways. HUDs can be utilized to deliver information to drivers to aid them in perceiving and reacting to possible obstacles in the roadway, allowing drivers to react more quickly and with greater distance between them and any obstacles, while also providing guidance for how drivers should react. Though current technology may not allow the full capability of the systems we investigated, the overall concept can be translated to HUDs within our current technological restraints to improve takeover performance in current driving automation systems.

TOR Preference

Results indicated that participants did prefer screen-relative and world-relative display graphics over the HDD graphic. This could be due to the ability of participants to keep their eyes on the road while receiving directions and situation information. Participants did prefer world-relative graphics over all other visual displays, possibly due to the novelty effect, but open-ended responses have not been fully evaluated.

Participant preferences of auditory cues were analyzed to investigate preference differences in auditory cues. Participant scores also indicated their preference for the tone with directional cue over the tone only and tone with the “Takeover Required” cue. This could have been due to the increase of information projected by the cue, as the tone and directional command cue provided the most auditory information out of the three cues. Participants received directional cues consistent with visual cues, giving multiple modalities of cues for correct actions. The tone with "Takeover Required" may have been perceived as a redundant cue, as participants may have interpreted the tone as a takeover cue.

Data collection for this study was conducted in February and March of 2020, which led to complicated factors due to the COVID-19 pandemic. The study was designed to run as a 3x3x3 factorial study where participants experienced a total of 30 drives with a combination of three visual, three auditory, and three haptic steering wheel conditions. The haptic conditions used a steering wheel that created a pulsed opposing output on the steering wheel if drivers turned the incorrect way (i.e., turn clockwise when the correct action would be counterclockwise), a small jerk (nudge) of the steering wheel in the correct direction of the steering action needed, or no haptic input as a control condition. However, due to the pandemic and shutdown, data collection for the required number of participants could not be completed. Because of the lack of participants and design of the study allowing us to do so without losing significant power, the haptic condition drives were removed from the analyses. Also, due to data collection not being completed for the intended number of participants, balancing of participant gender was not achieved, resulting in unequal numbers of male and female participants. Additionally, due to budget restrictions, full analysis of collected eye-tracking data was not conducted, although the data were collected and have been saved for potential future analysis. Future work may benefit from comparing results in this work with eye-tracking data to help leverage the use of HUDs in increasing SA and takeover performance metrics.

Conclusions and Recommendations

Though this study did not indicate effects of visual graphic display on participant SA, participant takeover performance did indicate positive results. Aligning with previous studies, the results showed that HUDs support safer driver reactions [8, 9]. Using HUDs provided greater context to the driving scene itself by projecting lane availability. Building on previous research on highway driving scenarios that projected lane availability [8], displays were created that indicated both lane availability and lanes that were unavailable and unsafe to drive in. From this, it was concluded that though driver SA may not have been affected by display type, drivers may benefit from increased roadway information displayed via use of a HUD.

From this work, a ground level evaluation of displays that aimed to increase driver SA during takeover was achieved. Future studies could benefit from expanding on this work's understanding of L3 conditional automated systems on highways. Future research could investigate a variety of time budgets and test different driving scenarios with higher traffic density. In addition to time budget, research may also benefit from focusing on longer drives, versus multiple short drives, to understand nuances and changes in driver SA during takeover. This study included a limited number of visual displays used in highway scenarios; thus, future work may investigate more use cases of bird's-eye view or displays indicating presence of other vehicles around the driver's vehicle, especially in cases where evasive maneuvers are required.

Additional Products

Education and Workforce Development Products

A PowerPoint presentation was created that outlines rapid prototyping and evaluation of automotive HMIs in virtual environments. This presentation provided an overview of the simulator, HMIs used, driving scenarios, and data logging information. Each section gave an overview of the scenario and HMI creation steps, presented problems and solutions during the study duration, and how data were reduced. The presentation then outlined lessons learned and guidelines to assist future researchers in conducting similar user studies.

Technology Transfer Products

After data collection and initial analysis was completed, this work was presented to the Industry Champion and associated team during Summer 2020. This work was submitted to the 2020 and 2022 Association for Computing Machinery International Conferences on Automotive User Interfaces (AutoUI) as full papers but was not selected for publication. A subsection of this work was presented at the 1st International Workshop on Extended Reality for Industrial and Occupational Supports (XRIOS) at the International Conference on Virtual Reality and 3D User Interfaces (IEEE VR) in 2022.

Data Products

Data from this work are organized in a centralized Microsoft Excel file. Data are organized by type: SAGAT data (SA), sim data (driving performance and takeover performance metrics and eye-tracking data), Qualtrics data (demographic and other information collected from participants), and acceptance data (data collected assessing participants' acceptance of the used HMIs). Data types are classified into two categories: *Cleaned*, which indicates data that have been reduced from raw and used for data analysis presented; and *Raw*, which indicates data that are in their original form as they were collected and have not been extensively reduced or sorted.

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