Using Human-Machine Interfaces to Convey Feedback in Automated Vehicles

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SAFETY RESEARCH USING SIMULATION
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Abstract

The next decade will see a rapid increase in the prevalence of partial and conditional vehicle automation, specifically SAE Levels 2 and 3. These automated systems are designed for specific operational conditions, such as driving on mapped highways with clear lane markings, and, within these defined contexts, can control both the speed and the lateral lane position of the vehicle. In these levels of automation, the driver is expected to act as the fallback in situations that exceed the operational capacity of the automation or during unexpected automation failures. A human-machine interface (HMI) that can both keep the driver aware of the driving situation and vehicle state and effectively ease control transitions is therefore very important. This study investigated how aspects of the vehicle HMI design, specifically feedback provided about the confidence of the automation and presentation of non-driving secondary tasks, influenced aspects of the takeover process. The results demonstrate the complexity of re-engaging a disengaged driver in the context of partially automated vehicles.

1 Introduction

1.1 Background

The next decade will see a rapid increase in the prevalence of partial and conditional vehicle automation, specifically SAE Levels 2 and 3 [21]. These automated systems are designed for specific operational conditions, such as driving on mapped highways with clear lane markings, and, within these defined contexts, can control both the speed and the lateral lane position of the vehicle. GM Super Cruise is a recent example of such a partially automated vehicle, able to control speed and lane position and allowing drivers to take their hands off the steering wheel.

In these levels of automation, the driver is expected to act as the fallback in situations that exceed the operational capacity of the automation or during unexpected automation failures. The automation must transfer control back to the driver in these situations, and therefore drivers must remain aware of the driving situation even though they are not controlling the vehicle. Much research demonstrates that humans struggle in sustained vigilance tasks [4]. A human-machine interface (HMI) that can both keep the driver aware of the driving situation and vehicle state and effectively ease control transitions is therefore very important.

The goal of the HMI in automation is to provide feedback to the operator [15]. Feedback can make the driver aware of low-level sensor function (e.g., sensing lane lines in the image below) and aid higher-level decision-making tasks that include control transitions to or from the automation. A variety of different HMIs can be found in current partially automated vehicles. Many, such as Tesla Autopilot shown below, present automation state and takeover information on a digital instrument cluster. Newer instantiations also utilize lights on the steering wheel, such as those on the Super Cruise in the image below, to convey both system confidence and requests for the driver to take over.

Figure 1. Tesla Autopilot (left) and GM Super Cruise (right)

1.2 Objectives and Research Questions

This project had two objectives. First, we investigated the effect of providing real-time feedback about the confidence of the automation through the vehicle HMI. Second, based upon a basic attentional effect known as the gap effect, we examined whether extinguishing a non-driving secondary task prior to a takeover request speeds transition of control. The following sections describe the approach and results for each of these research goals. Section 2 provides results corresponding to automation feedback delivered through the vehicle HMI, and Section 3 describes the effect of extinguishing a non-driving secondary task prior to the initiation of the takeover process.

2 Human-Machine Interface Design to Convey Automation Feedback

2.1 Introduction

With the presence of automated capabilities growing in the automotive industry, it is imperative that the human operator remain at the forefront of research, design, and implementation. Since the beginning of the automotive era in the early 20th century, humans have played a very active role in driving. However, as vehicles become increasingly automated, humans are tasked with the somewhat unfamiliar and challenging role of supervision while operating a vehicle. SAE level 3 automation, referred to as conditional automation, has the ability to control the lateral (lane position) and longitudinal (speed) position of the vehicle [21]. However, when the capabilities of the automation have been exceeded, responsibility falls on the driver to take control in a safe and timely manner.

Regaining control requires that the driver be aware of the environment, surroundings, and automation status before the takeover is necessary. However, with the introduction of distracting tasks while using automation, sustained attention to the driving environment becomes increasingly difficult for some users. Thus, it is critical that the driver maintain a stable and accurate awareness of his/her surroundings at all times. Merat et al. [12] define multiple levels of control and attention when working with automation: in the loop (in physical control and monitoring the driving situation); on the loop (not in physical control but monitoring the driving situation); and out of the loop (not in physical control and not monitoring the driving situation). It is commonly suggested that increasing levels of automation likely reduce interactions with, and control of, certain facets of the driving task; this, in turn, can potentially compromise the driver’s ability to recognize, process, and respond to safety-critical events in a timely and controlled fashion [12, 14]. Therefore, to keep a driver “on the loop” while operating a conditionally automated vehicle is a significant component in developing effective automated systems that maintain appropriate attentional resources.

The HMI is the communication and cooperation link between the vehicle and the driver. It is critical for building trust, mental models, and expectations, along with maintaining the driver's situation awareness by transmitting important information on the surrounding environment and automation status [6]. Because the only communication between the driver and automation is through the user interface, there is extreme difficulty in designing an interface that conveys all the needed information without the potential of increasing cognitive workload on the driver [5, 7, 14]. The most effective automated systems ensure the driver knows when and where they are in charge, along with when and where they can safely rely on the system and turn their attention to secondary tasks [6, 11, 12].

One important role of HMIs is to provide feedback about system state. Multiple studies have found that providing drivers with accurate feedback about the automation's reliability facilitates more appropriate trust [2, 6, 7]. The overall transparency of a system that provides accurate and useful feedback can greatly reduce the frequency of misuse and disuse; little trust in a system may lead the operator to disable the automated functions, while over trust in a system can result in complacency effects [7, 9]. Automation complacency, often resulting from automation that is highly but not perfectly reliable, can contribute to a drivers' lack of monitoring and, therefore, detection of automation failures [14]. Parasuraman et al. [16] exhibited complacency effects resulting in poorer monitoring when automation reliability was high and unchanging; these effects were eliminated when reliability was variable between high and low. Similar research found a significant effect in conveying uncertainty information to the driver of a partially automated vehicle [1, 2, 23, 26]. In one such example, the uncertainty information appeared as a face with an uncertain expression and hand gestures; this was displayed to the driver in the uncertainty group when the automated system became uncertain, or less confident, in its abilities. Between the uncertainty group and the control group (receiving no uncertainty information), those in the uncertainty group were more likely to recognize the possibility of automation fallibility [2]. These findings demonstrate that by displaying uncertainty information continuously, operators are more likely to understand the limitations of the automation and develop more accurately calibrated trust.

Research has found that the role of passive monitoring combined with the responsibility of other tasks tends to increase reliance on the automation [9, 11]. Similarly, findings suggest that some drivers exhibit a “primary task reversal” in which the driver quickly prioritizes a secondary task at the expense of the driving task [3]. This resulted in inattention to automation warnings because it was no longer considered to be the primary task by the operator. However, as noted previously, research found that providing uncertainty information encouraged a more appropriate allocation of attention to the driving task rather than to the secondary task [1, 2]. The primary goal of this study was to understand whether providing uncertainty information via an automated vehicle HMI improves reliance, trust, and subsequent takeover performance.

2.2 Research Question and Hypothesis

- Does continuous feedback, compared to discrete feedback, of automation certainty improve the operator’s trust, performance, and acceptance in using the automation?

We hypothesized that by providing uncertainty information continuously, drivers would be better prepared to respond to a takeover request (TOR), resulting in faster response times (RTs) than when they did not receive uncertainty information. Moreover, the effect of unimodal (visual) versus multimodal (visual and auditory) feedback in the continuous conditions is expected to result in faster, more controlled responses to TORs. Further, we expect to see higher trust-ratings of the automation from those receiving continuous feedback than from those receiving discrete feedback.

2.3 Method

2.3.1 *Experimental Design*

A 3 x 2 between-subjects design was used for this study. The between-subjects variable was the type of feedback conveying the automation's confidence (discrete, continuous visual, or continuous visual and auditory). This was done by displaying the automation's certainty via the instrument panel. Each participant was randomly assigned to one of the three groups.

2.3.2 *Participants*

Sixty male and female adult licensed drivers (ages 25-40) participated in this study. All participants had at least three years of driving experience, driving at least 2,000 miles annually or three times per week, and were in good general health. Participants were recruited from the National Advanced Driving Simulator (NADS) IRB-approved registry and contacted by phone or email. Participants were provided a general overview of the study and screened for eligibility. They were told they would be compensated $35 for participation in the study and could receive an additional $15 for good performance on the trivia task. Participants were asked to avoid the consumption of alcohol or other drugs not prescribed by a physician in the 24 hours preceding their visit.

2.3.3 *Apparatus*

This study used the miniSim at NADS. The NADS miniSim configuration uses three 42" displays with steering, pedals, shifter, and seat from an actual vehicle. This configuration also features high-fidelity surround sound audio, an LCD-based "glass dash" instrument panel and a touch-screen-based operator console.

Figure 2. NADS miniSim driving simulator

2.3.4 Human-Machine Interface

The interface displayed an icon located between the speedometer and tachometer in the instrument panel. For all three conditions, a green road symbol indicated the engagement of automated features. A red steering wheel indicated a takeover request. For the two continuous conditions, the interface included a colored “confidence bar” indicating the automation’s current level of capability. Participants were randomly assigned to one of the three conditions: discrete, continuous visual, or continuous visual and auditory, described in detail below.

- **Discrete**. This served as the baseline condition, and drivers did not receive any changing information regarding the automation’s confidence. While the automated system was activated, the road icon appeared solid green (Figure 3). When the system exceeded its capabilities, drifting almost completely out of its lane, and administered a TOR, the road icon was replaced with a red steering wheel coupled with an audio warning to take over.

Figure 3. Automation displays activation with solid icon (left); automation requests takeover with solid icon and auditory warning (TOR) (right)

- **Continuous Visual**. The automation provided the driver with continuous feedback regarding its confidence in lane keeping. When the system was certain of its capabilities, the road icon was displayed in solid green with a full green bar underneath (Figure 4). As the automation began to lose detection of a lane line, thus reaching its limitations (5 seconds before TOR), the right lane line on the icon disappeared; the confidence bar became less full and yellow. A TOR was administered when the automation exceeded its capabilities and drifted out of its lane onto the right shoulder: the road icon was replaced with a red steering wheel icon, the confidence bar emptied to the "minimum" level in red, and the driver received an audio warning to take over.

Figure 4. Automation displays full confidence in solid icons (left); automation displays mid-confidence in solid icons (center); automation displays low confidence with solid icons and auditory warning (TOR) (right)

- **Continuous Visual and Auditory**. The interface for this condition provided the same information as the continuous visual condition, detailed above. The difference between the two conditions was the addition of an auditory chime when the automation dropped to mid-confidence (Figure 5). In further sections, this condition is also referred to as "AV".

Figure 5. Automation displays full confidence in solid icons (left); automation displays mid-confidence in solid icons (center); automation displays low confidence with solid icons and auditory warning (TOR) (right)

2.3.5 Driving Scenario

Practice Drive: The practice drive lasted approximately 10 minutes, during which participants acclimated to the simulator and the transfer-of-control process. Participants began by driving manually for about three minutes until instructed to transfer into automated mode. Transferring from manual to automated mode, and vice versa, was similar to how cruise control works in vehicles. Participants pressed the automation button on the steering wheel to transfer control from manual to automation. Participants then returned to manual mode by steering or depressing the brake or automation button. When driving manually, there was no icon displayed on the instrument panel. Participants were informed that the automation was engaged when they pressed the automation button on the steering wheel and the green icon appeared on the instrument panel. There was also an audio chime when the automation became engaged or disengaged. Participants encountered two TORs (automation drop-out) during this drive.

Study Drive: The study drive lasted approximately 40 minutes (Figure 6). The rural road network consisted of two to four lanes of separated interstate with a speed limit of 65 mph. Drivers were instructed to activate autodrive when they reached 65 mph. While the vehicle was in automated mode for the majority of the drive, participants engaged in a trivia task on a tablet to their right. Throughout the automated driving segments, drivers experienced eight takeover situations in which they needed to retake control from the automation as it encountered events that exceeded its performance limitations. Six of these takeovers were accompanied by a TOR (Figure 7), while the remaining two were "silent failures," giving no TOR prior to the automation failure (Figure 8). Drivers in the two continuous conditions also encountered four "false alarms" in which the automation icon displayed mid-confidence for 5 seconds before returning to full-confidence (Figure 9). These displays are detailed in the following section.

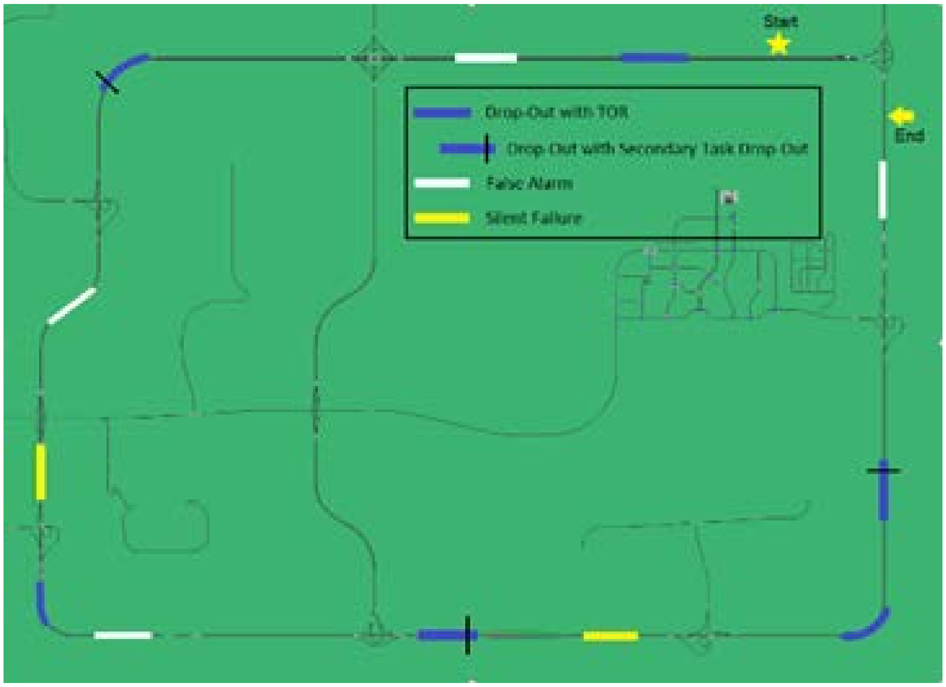


Figure 6. Map of the study drive, including locations of automation drop-outs with TOR (blue), silent failures (yellow), false alarms (white), and automation drop-outs with and without secondary task drop-out (blue with/without black line)

2.3.6 Events

Takeovers: Throughout the drive, participants experienced eight takeover situations in which the automation failed to detect lane lines and began to drift out of its lane (imitating a failure of the lane centering system). Participants were expected to regain manual control of the vehicle as quickly and safely as possible by steering or depressing the brake or automation button on the steering wheel. If the driver failed to regain manual control six seconds after the TOR, the simulation was designed to correct the vehicle's position back to the center of the lane and continue in autodrive. Following takeover events in which the driver takes over manual control, a voice recording instructed participants when to re-engage autodrive.

Six of the eight takeover situations consisted of an automation drop-out; in these events, participants received a TOR upon automation failure. The remaining two takeover situations consisted of silent failures, as if the automation were unaware of its limitations in that situation; participants did not receive any changing information regarding the automation's confidence and there was not a TOR. If the driver failed to regain manual control in either of these events, the simulation was designed to correct the vehicle's lane position and continue in autodrive. There were also four false alarm events in which the two continuous conditions received mid-confidence feedback for 5 seconds until returning to full-confidence. The discrete condition did not encounter this event. These events are detailed in Table 1. The final row in Table 1 is further explained in Section 3.

Event	**Continuous** (Visual & Visual/Auditory)	**Discrete**
Drop-Out (6)	Automation failure Received mid-confidence feedback 5 seconds before TOR	Automation failure Received TOR at time of failure
Silent Failure (2)	No mid-confidence or takeover feedback was given when automation failed	No takeover feedback was given when automation failed
False Alarm (4)	Received mid-confidence feedback without automation failure Returned to full-confidence after 5 seconds	Did not encounter this event
Secondary Task Drop-Out (3)	The tablet screen went black 300 ms before TOR	The tablet screen went black 300 ms before TOR

Table 1. Events

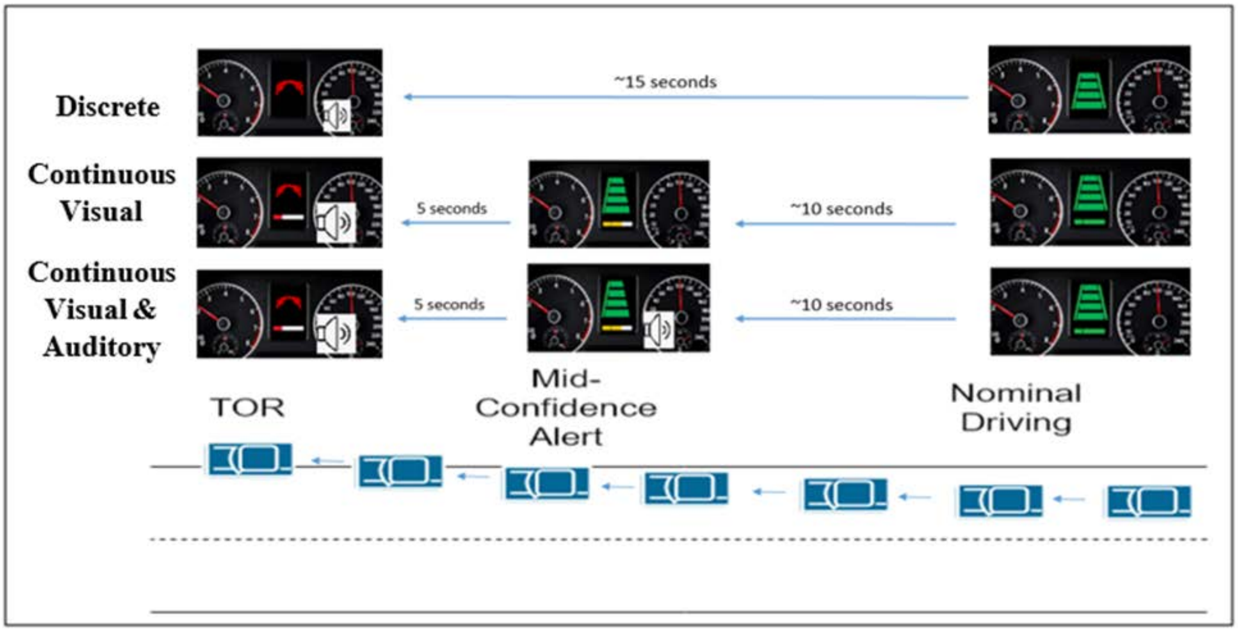


Figure 7. Timeline of automation drop-out event

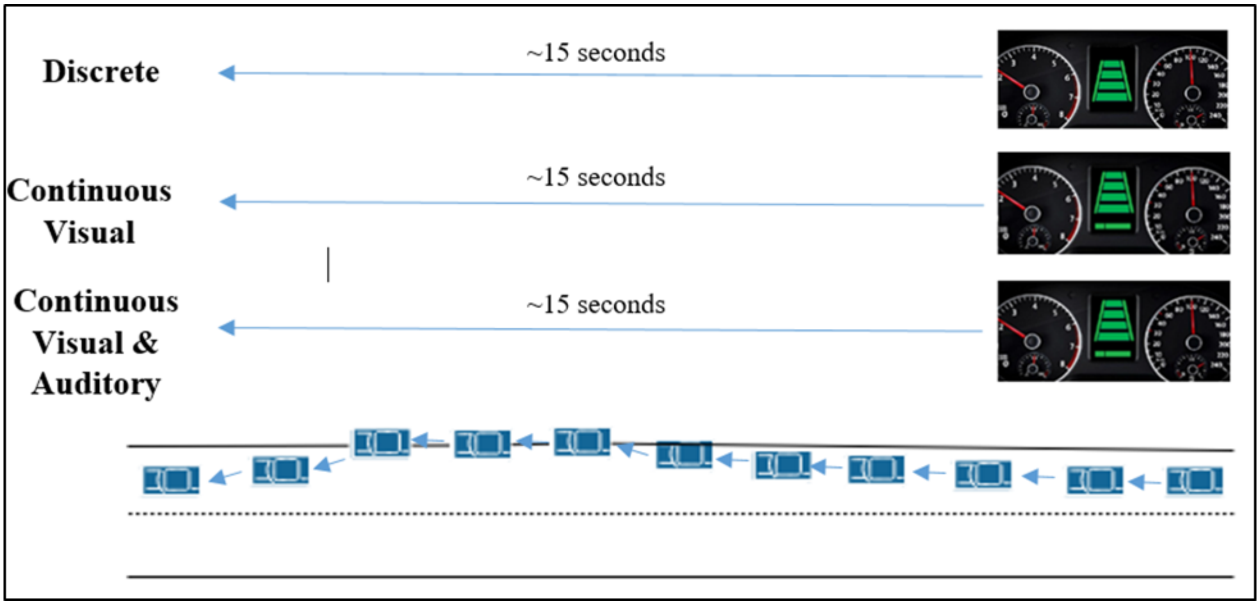


Figure 8. Timeline of silent failure event

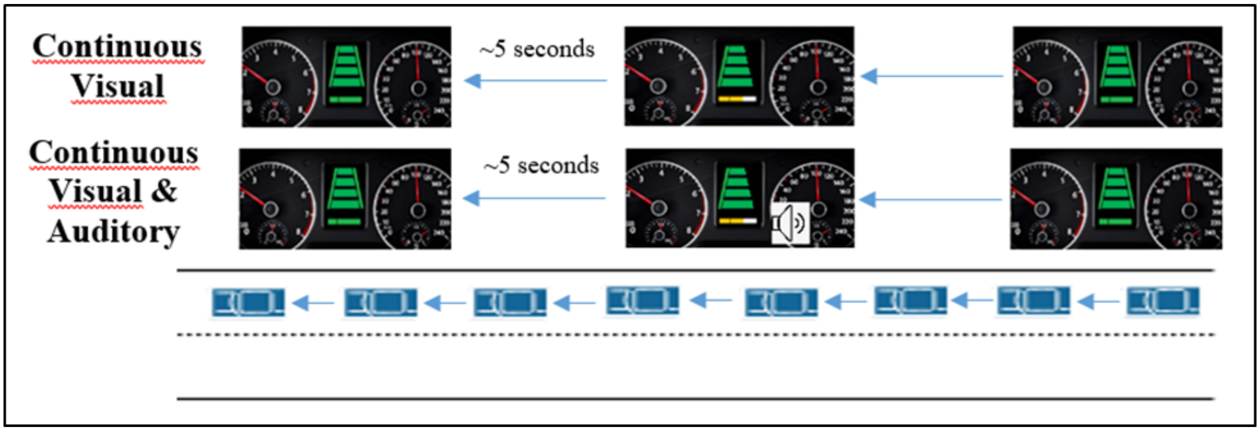
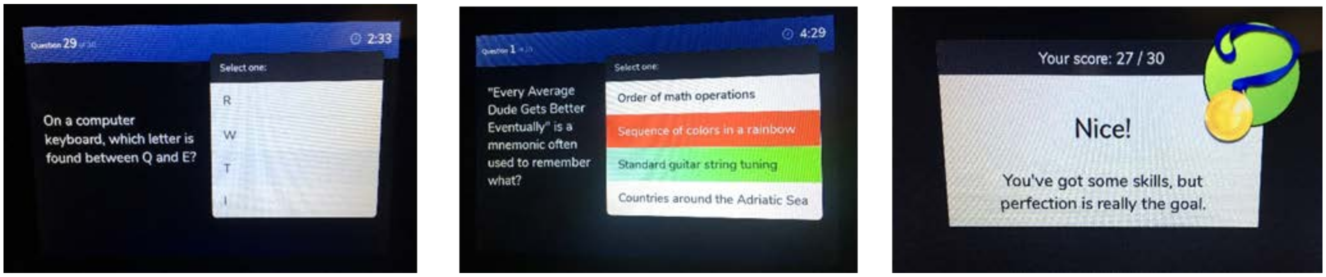


Figure 9. Timeline of false alarm event

2.3.7 Non-Driving Secondary Task

While the automated system was in use, participants were instructed to complete a secondary task of trivia on a tablet located on a stand to their right, similar to the placement of the control panel in a vehicle. Each round of trivia consisted of 30 random questions and had a 5-minute time limit. At the completion of each round, participants reported their total correct to the research assistant in the room. In order to further encourage participants to be actively involved in the trivia task, they were told that there would be an additional $15 compensation for cumulative scores over 150; in reality, the bonus compensation was a deception, and all participants received the “extra” $15.


Question 29
2:33
On a computer keyboard, which letter is found between Q and E?
Select one:
R
W
T
I

Question 1
4:29
"Every Average Dude Gets Better Eventually" is a mnemonic often used to remember what?
Select one:
Order of math operations
Sequence of colors in a rainbow
Standard guitar string tuning
Countries around the Adriatic Sea

Your score: 27 / 30
Nice!
You've got some skills, but perfection is really the goal.

Figure 10. The secondary task consisted of 30-question rounds of randomized trivia questions.

2.3.8 Procedure

Upon arrival at NADS, located in the University of Iowa Research Park, prospective participants were verbally reminded of the purpose and procedures involved in the study. Following a verbal review of the informed consent, participants were asked to carefully read the document; members of the research team provided time to answer any questions they had. Participants were considered enrolled in the study after they signed the informed consent document; a copy of this document was given to participants following the completion of the study drive. Participants also completed a payment form and signed a video release form. After the completion of these documents, participants were shown a brief PowerPoint presentation restating the purpose and procedure of the study. The presentation also provided an explanation of the features they would be using (e.g., automation activation button) and various tasks they may run into (e.g., TORs). Finally, participants were asked to complete a short questionnaire regarding general demographics and their current trust in automation.

Next, participants were escorted to the simulator, where they were provided a brief overview of the cab layout and given time to adjust the seat and steering wheel. After a reminder of the general simulator procedure, participants completed a practice drive followed by a wellness survey. If there were no indications of possible simulator sickness, the participants proceeded to the study drive. At the end of the study drive, the participants were escorted out of the simulator and to a private room, where they completed a second wellness survey. They were provided a second, more extensive questionnaire about demographic information, the degree of perceived risk/reliability/trust during the drive, and general perceptions of automated vehicles. Next, participants were read the debriefing statement expressing gratitude for their participation, explaining the true nature of the compensation scheme, and requesting they do not discuss specifics of the study until a specified date. The members of the research team completed the payment voucher, and participants were free to go.

2.4 Results

2.4.1 Dependent Measures

- **Look-up time***:* Video data was used to code the first look forward after the TOR was presented. Video data was also coded to determine the direction of the first glance, being either forward or at the instrument panel.
- **Response to takeover**: Data collected from the simulator was used to record RTs following TORs. This included the time from the issuance of the TOR to the time the driver regained full manual control, either by steering or by depressing the brake or automation button.
- **Response behavior**: Data was used to analyze lateral and longitudinal deviation following a TOR.

  Trust and acceptance: A post-drive questionnaire was administered to measure the driver's overall trust and comfort in using the automation. Drivers were asked about their acceptance, satisfaction, and likelihood of using automated technology while driving. They were also asked about the usefulness and comprehensibility of the feedback that was provided throughout the drive.

In comparing TOR to look-up times, a pairwise t-test showed significant effects when comparing discrete and AV conditions ($p = 0.00041$). A pairwise t-test also showed significant effects when comparing discrete and visual conditions ($p= 0.01844$). There was no significant difference between the visual and AV conditions. As hypothesized, results showed quicker look-up times after TOR for subjects in the visual and AV conditions over the discrete condition.

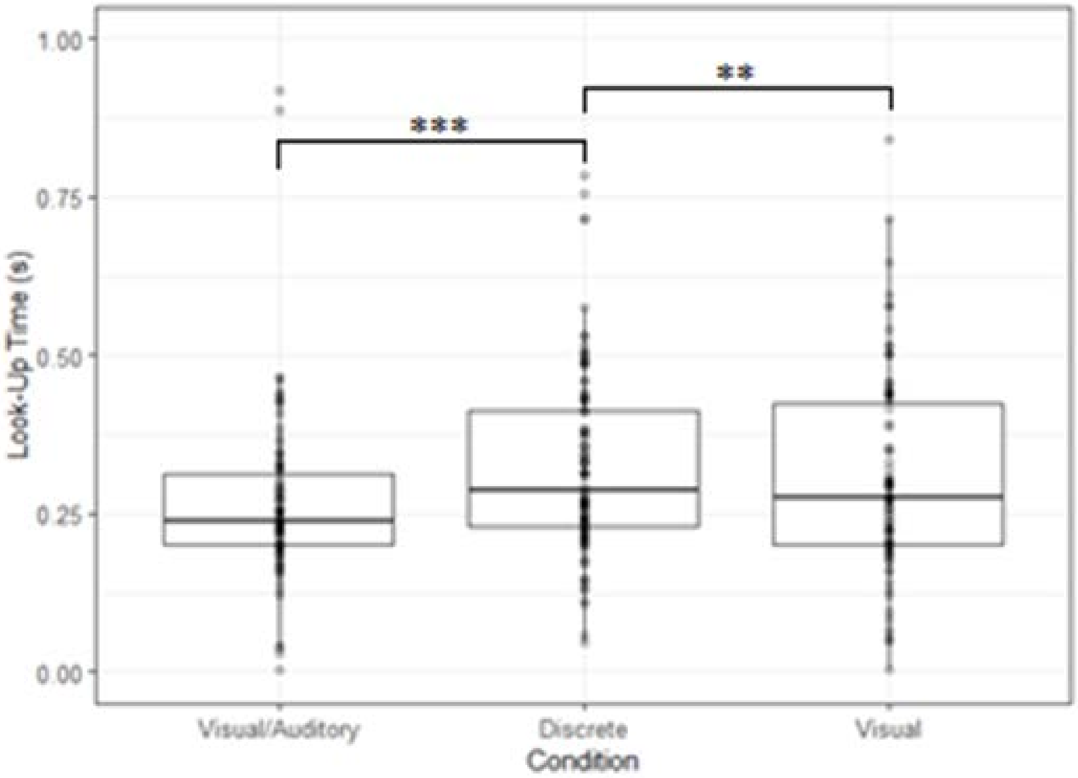


Figure 11. Boxplot showing look-up times across conditions

Additionally, there was a significant difference in takeover time between all three conditions (p = 0.0472). Takeover times were overall quicker in the visual and AV conditions than in the discrete condition. Further, a pairwise t-test showed a significant effect on takeover time between the discrete and AV conditions, with AV resulting in faster takeover times (p = 0.0085). A pairwise t-test also found a significant effect on takeover time between the visual and AV conditions, with AV resulting in significantly faster times (p = 0.0026).

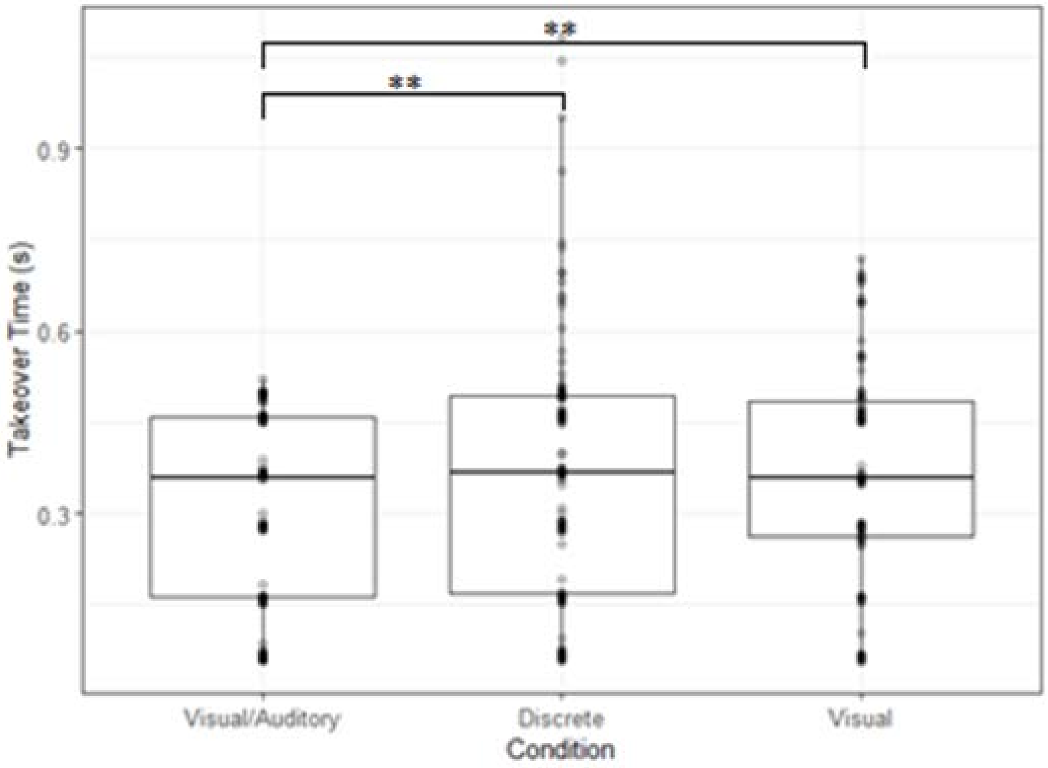


Figure 12. Boxplot showing takeover times across conditions

Results did not indicate significance between condition type and steering RT. Contrary to findings indicating an advantage to the continuous visual and/or visual/auditory feedback, steering RT appeared to be faster in the discrete condition. However, the slower steering RT could be a result of the continuous group being more prepared to intervene, whereas the discrete group may have had a more instinctual response to the TOR, thus reaching for the steering wheel as their initial response.

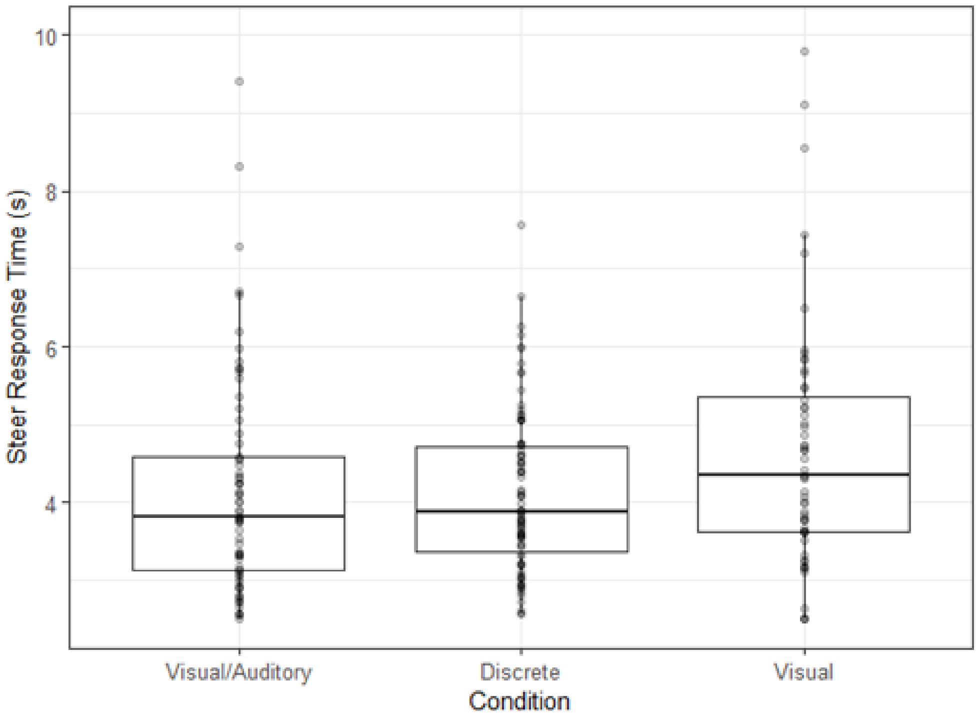


Figure 13. Boxplot showing steering RT across conditions

In terms of overall comfort with using the automated system, analysis of the post-drive questionnaire revealed that participants using the discrete condition reported higher feelings of comfort and trust in the system. The discrete group also reported feeling more comfortable when transferring the vehicle into autodrive than the visual and AV groups.

As mentioned earlier, subjects in all three conditions received two silent failure events. In these events, the car gradually drifted out of its lane onto the right shoulder. The amount of drift in this event was equivalent to that of the six takeover events, only it did not administer a TOR. If the participant failed to manually take over and correct the vehicle's lane position within 5 seconds of maximum lane deviation, the simulation was designed to re-center the vehicle within its lane. When automatically re-centering, the vehicle quickly jerked back to its correct position in the lane. The sudden and somewhat aggressive movement of the vehicle in this situation caused several participants to look up after the vehicle re-positioned itself (63/120 silent failures). There were also four participants that took manual control after the vehicle suddenly re-positioned itself (7/120 silent failures). One question on the post-drive questionnaire asked: “How likely is it that you would have taken back manual control without the automation alerting you of a failure?” Participants rated the likelihood of intervening in such situations on a 1-7 scale (1= Very Likely, 7= Very Unlikely), averaging 3.88 across all participants. However, contrary to the average response, only one participant responded correctly and within the time limit for both silent failures. All other participants failed to recover the failing automation before the vehicle corrected its lane position.

Video data was also used to determine the initial eye position at the time of the TOR. Looking down indicates that the driver was looking at the trivia screen at the time of the TOR; looking up indicates that the driver was looking around, forward, or at the instrument panel at the time of the TOR. Finally, there were a total of 25 takeovers before the TOR, indicating that the driver was aware of the automation failure and voluntarily took back manual control before the TOR was presented. These results show a clear difference in gaze behavior between the three conditions (more specifically, between the discrete and AV conditions).

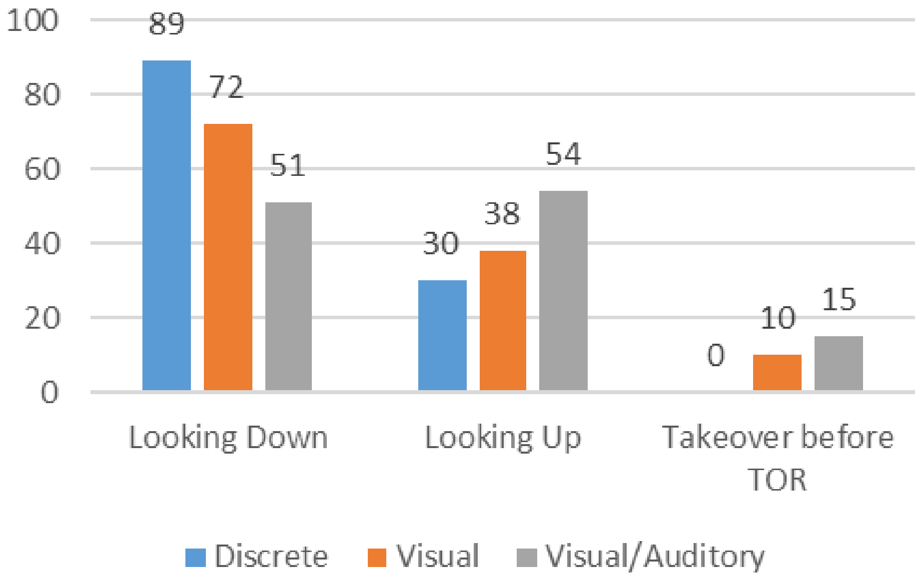


Figure 14. Chart showing the initial eye position at the time of TOR

Through video analysis, we were also able to determine where the first glance was directed: either at the instrument panel or at the road. The results show that the continuous condition acknowledged the purpose of the display. Although we were not able to objectively determine whether they found the display useful or informative to any extent, it is encouraging to know the drivers were looking at it. Moreover, the first look after TOR could be a possible explanation for the difference in steering RT between conditions; however, further research is necessary to determine this.

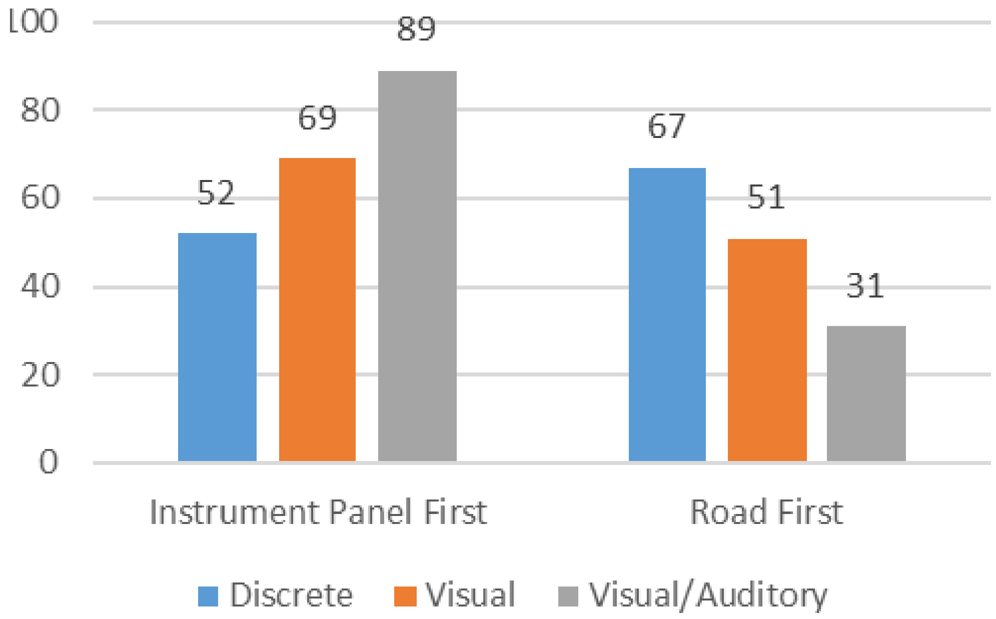


Figure 15. First look after takeover request

2.5 Discussion

The multiple-resource theory supports parallel processing in that input information is apportioned to various sensory modalities, aiding in more efficient control of cognitive workload [24]. With the increasing degree of visual demand placed on secondary tasks while operating an automated vehicle, it is sensible to infer that visual feedback may not appear salient enough to redirect one's attention to the driving scene. The use of multimodal warnings, however, has been shown to increase the sense of urgency in a situation requiring a driver takeover [3, 13]. Results from this study support this theory because the AV condition produced significantly faster RT.

As noted previously, a "primary task reversal" occurs when a subject is given an alternate task and learns to devote a significant amount of attentional resources to this task [3]. This did occur in a number of our participants, resulting in them completing a trivia question before responding to the TOR. The cases where we exhibited the primary task reversal accounted for many of the outliers in both the look-up times and RT. The degree to which a driver prioritizes the secondary task could be heightened in the context of a driving simulator, given that there is significantly less risk than in a real-world driving situation.

According to the results found in this study, there appears to be a clear advantage to continuous feedback in terms of maintaining awareness of the system’s state and surroundings. Both continuous groups were quicker to look up and take manual control of the autodrive after the TOR was administered. Further, the fact that the discrete condition responded more quickly to move the steering wheel could be an indication of lack of preparedness or an instinctual response to recover the vehicle using the steering wheel.

Research on the design of HMI in vehicles is more pertinent than ever; understanding what works and what doesn’t and what drivers like and what they don’t is only the beginning of designing for effective, communicative, and cooperative interactions between the operator and the automation. Although the discrete condition showed higher overall trust and comfort with the automation, the continuous condition may have held a more accurate calibration of trust in the system, granted the system was not perfect.

Further, it is slightly disconcerting to know that many of the participants were at least moderately confident in their ability to regain control of the vehicle had the automation not warned them of a failure. This is an important factor to consider when understanding the human’s role in automation because the results show an obvious distortion between the driver’s idea of their own ability and the reality of their own ability.

3 Gap Effect and Secondary Task Disengagement

3.1 Introduction

A significant challenge for HMI design for highly automated vehicles is difficulty in disengaging from a secondary task when alerted for a takeover. Attention cannot be relocated until it has been disengaged from the initial focal point [10]. Moreover, saccadic eye movements are not carried out until attention has been disengaged [19, 25]. This process, known as the gap effect, has been found to be most effective when the fixation point is removed 200 ms before the appearance of the target point, thus providing sufficient time to disengage from the fovea and redirect attention to the target point [8, 17]. In the context of an automated vehicle where a driver is engaged with a secondary task and receives a takeover alert, the driver must first disengage from the secondary task before shifting attention back to the driving scene [22].

Attentional disengagement is thus a critical component in the ability to monitor and recover vehicle behaviors when necessary. Previous research has demonstrated a positive impact in facilitating the disengagement and reallocation of attention by removing the stimulus at the fixation point prior to the demand of attentional disengagement; this temporal gap between fixation point offset and target onset is known as the gap effect [22, 25]. Fixation offset has also been found to speed performance by increasing response readiness, thus serving as an effective warning signal [18, 20, 22]. One goal of the present study is to understand whether shifting attention back to the driving scene can be expedited by removing a secondary task at fixation.

3.2 Research Question and Hypothesis

- Does extinguishing the secondary task prior to a TOR result in faster response times than when the secondary task remains on throughout the takeover?

We expect video data to reveal quicker look-up times and RTs on TORs after the secondary task has been removed (referred to as fixation offset or gap) than when it remains on. The time it takes to transfer gaze from the secondary task to the road ahead after a TOR will be compared between trials of fixation offset versus not; Figure 16 provides further detail on the timeline of this.

3.3 Method

3.3.1 Experimental Design

A 3 x 2 mixed design was used for this study. The between-subjects variable was the type of feedback conveying the automation's confidence (continuous visual, continuous visual and auditory, or discrete). This was done by displaying the automation's certainty via the instrument panel. Each participant was randomly assigned to one of the three groups. The within-subjects independent variable was the drop-out of the secondary task versus no drop-out.

3.3.2 Participants

See Section 2.3.2 for details on participant eligibility and recruitment.

3.3.3 Apparatus

See Section 2.3.3 and Figure 2 for details on the NADS miniSim.

3.3.4 Driving Task

See Section 2.3.5 and Figure 6 for details on the driving task.

3.3.5 Events

See Section 2.3.6 and Table 1 for details on the drive events.

3.3.6 *Non-Driving Secondary Task*

See Section 2.3.6 for details on the secondary task.

As mentioned previously, the within-subjects independent variable included the secondary task. On three of the six automation drop-outs, the tablet screen blackedout 300 ms prior to the TOR. On the other three drop-outs, the tablet screen remained on. By extinguishing the focal point, we hypothesized that participants would disengage their attention sooner, resulting in faster look-up times and RTs to the TOR. See Figure 10 for visual examples of the secondary task.

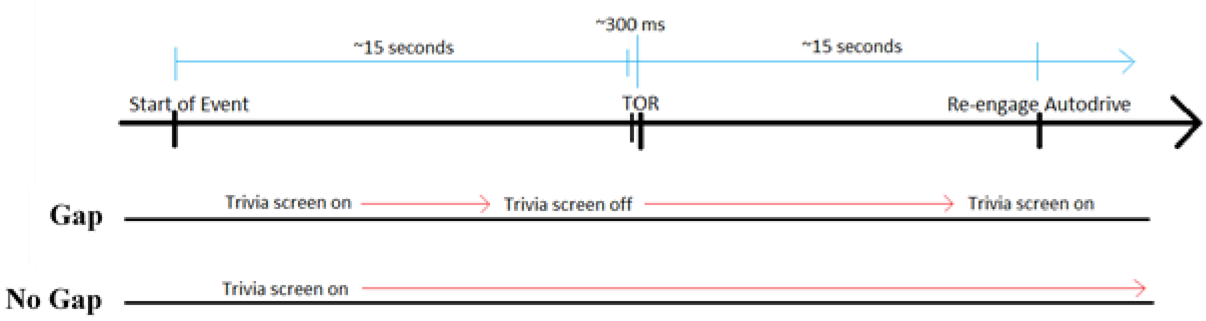


Figure 16. Gap Conditions

3.3.7 *Procedure*

See Section 2.3.8 for details.

3.4 Results

3.4.1 *Dependent Measures*

- **Response to takeover:** Data collected from the simulator was used to record RTs following TORs. This included the time from the issuance of the TOR to the time the driver regained full manual control, either by steering or by depressing the brake or automation button.

- **Response behavior:** Data was used to analyze lateral and longitudinal deviation following a TOR.
- **Secondary task drop-out:** Video data was used to compare RTs between automation drop-outs with a secondary task drop-out versus no secondary task drop-out.

As we hypothesized, look-up times were significantly faster for those in the gap condition than those in the no-gap condition (p = 0.000274), supporting the gap effect theory. However, contrary to our initial hypothesis, the actual RTs (takeover time and steering RT) were negatively impacted in the gap condition. The no-gap condition showed significantly faster takeover times (p = 0.00318) and steering RTs (p = 0.0763) than the gap condition.

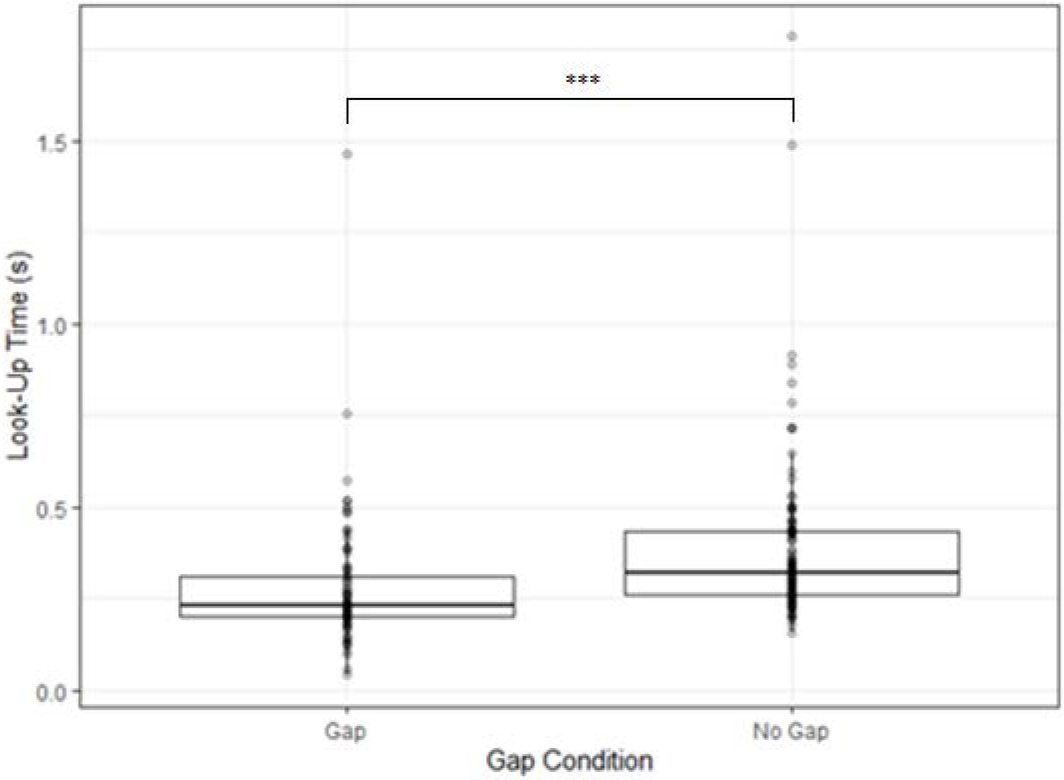


Figure 17. Time to look up from secondary task

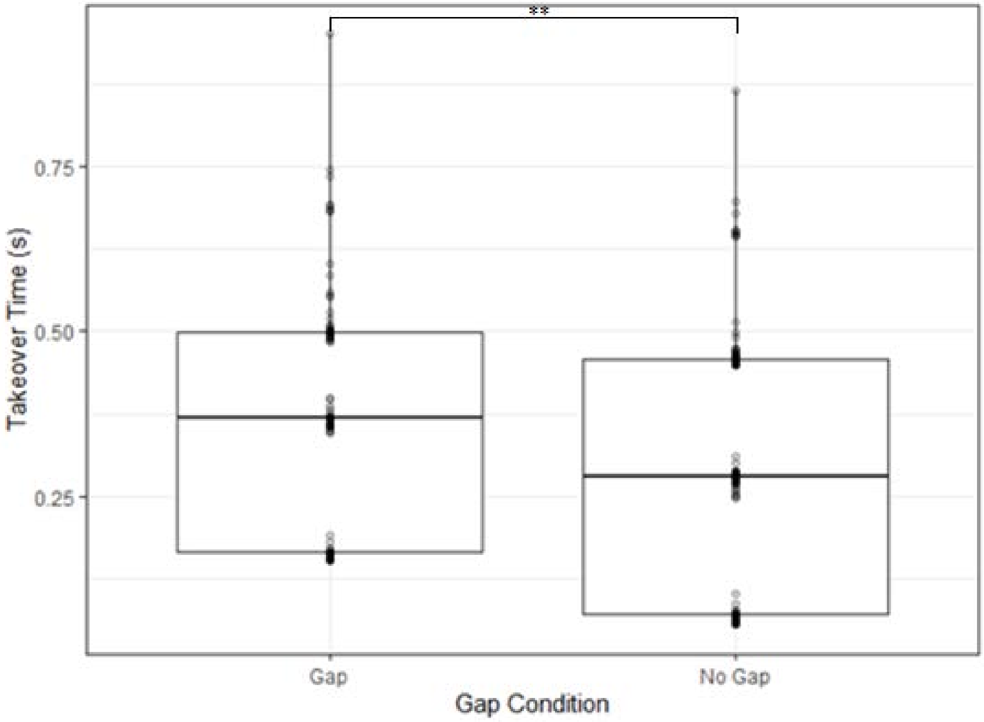


Figure 18. Time to disengage automation

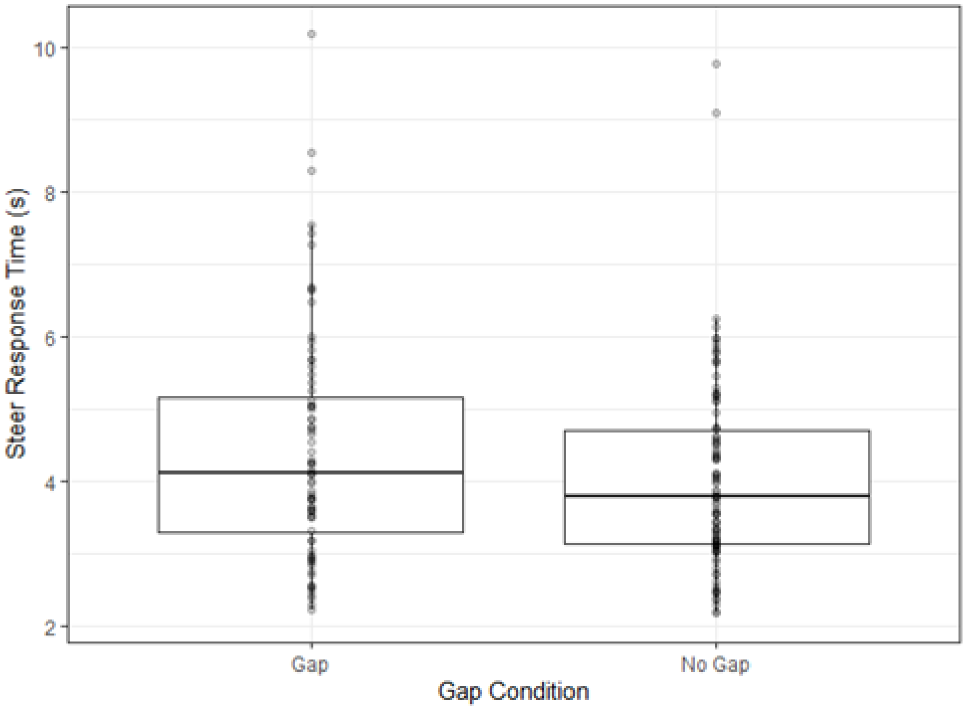


Figure 19. Time to initial steer response

3.5 Discussion

While these results demonstrate an effective release of a fixation point, they do not necessarily show effective attentional engagement. Naujoks [13] found task switching to involve two main components: (1) lag interruption, the time between onset of HMI and NDRT interruption (defined by the time at which the driver redirects attention away from the NDRT); and (2) interruption length, the time needed to process the HMI message. Further, results found that NDRT interruptions are often followed by a delayed re-uptake of the primary task.

Although these results demonstrate an alternative method for hastening the re-direction of attention, it may also indirectly inhibit the latter steps of processing in a time-critical situation. A potential explanation for the slower takeover and steering RTs could be confusion resulting from the blanking of the trivia screen. Subjectively speaking, video data shows a number of drivers looking confused or concerned when they notice the trivia screen blanking; this, in turn, could explain the faster look-up times and slower RTs found in the gap condition.

As noted previously, a “primary task reversal” occurs when a subject is given an alternate task and learns to devote a significant amount of attentional resources to this task [3]. This did occur in a number of our participants, resulting in them completing a trivia question before responding to the TOR. However, participants did not have the option to finish a question in the gap condition because the trivia screen turns off just before the TOR.

While we did find significant effects between the gap and no-gap conditions, there is still a need to further investigate the various factors that could be contributing to the differences in RTs. It is difficult to say how drivers would respond differently, if at all, if they were informed beforehand that the trivia screen may blank at certain times; this could potentially reduce some confusion relating to the screen. Future evaluation of this data will also attempt to examine patterns in sequences of gaze behavior prior to and following a TOR.

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