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From young to old: The effects of information presentation type, multimodal display, and age on situation awareness and processing time in automated vehicles

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A B S T R A C T

Research has revealed that conditionally automated vehicles can adversely affect situation awareness, a crucial factor in ensuring a safe transition of driving control during takeover, particularly for older adults. The objective of this study was to design and test more complex multimodal interfaces capable of delivering critical real-time road information, including obstacle locations, statuses, and lane availability, to effectively assist drivers who may experience age-related cognitive and physical declines, when navigating complex automated systems. This study investigated the effects of displays (single tactile, and visual and tactile combined), information presentation type (instructional, informative, baseline), and age (older and younger adults) on participants' takeover performance (i.e., information processing time and situation awareness). In general, the utilization of informative information resulted in an enhancement of drivers' situation awareness and information processing time, compared to when using the instructional information type. Moreover, multimodal displays were associated with faster processing speeds compared to unimodal displays. However, no significant main effect of the display was observed on the level of situation awareness. Likewise, there was no discernible age-related disparity in situation awareness levels. Yet, younger adults exhibited shorter information processing times than older adults. This research aims to improve situation awareness and processing time to help drivers, especially older adults, prevent time-critical accidents during the takeover process in automated driving. The findings from this study may inform the design of next-generation in-vehicle human–machine interfaces.

1. Introduction

According to the World Health Organization (WHO), the nation is experiencing an aging trend, with projections predicting a 50% increase in the older adult population (aged 65 or above) by the year 2050 (Khan et al., 2021). Consequently, there is likely to be a rise in the number of older adult drivers on the roads. To note, driving encompasses various complex components, such as sensory perception (e.g., visual, auditory, and tactile), cognitive abilities (e.g., memory, attention, and information processing), and psychomotor skills (e.g., strength and dexterity performance), and, all of which can be adversely impacted by naturally occurring age-related declines (Mihal & Barrett, 1976; Panek et al., 1977; Peng et al., 2022; Wickens et al., 1987). These declines can

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significantly impact safe driving in older adults compared to younger adults, given that these age-related declines may impair drivers' ability to perceive critical objects in the environment (e.g., pedestrians, road signs, and/or vehicles), process sensitive information and make decisions related to the driving task, and execute motor functions to avoid abrupt accidents (Bolslad, 2001; Karthaus & Falkenstein, 2016). Age-related declines can ultimately limit an older adult's ability to maintain independence in mobility, hindering them from being able to live active lives, leading to a reduction in their well-being (Kadylak et al., 2021). Fortunately, advancements in automated vehicles are also expected to become prevalent on roads soon and may even be able to help prolong older adults' independence in mobility by taking on most of the responsibilities in the driving task, allowing drivers to almost disengage entirely from the driving task (SAE, 2021). However, it is important to note that current automated vehicles are not fully autonomous (e.g., Level 3 automation) which introduces certain constraints, as drivers can encounter situations where they need to take over control of the vehicle, often in intricate circumstances, such as during inclement weather or near construction zones (SAE, 2021).

The takeover process, depicted in Fig. 1, is a complex process consisting of at least two phases: the signal response and post-takeover phases. In the signal response phase, drivers need to quickly perceive and process the takeover requests (TORs), redirect their attention to the driving environment, and become aware of their surroundings, while physically readjusting their body back to the driving position. In the post-takeover phase, drivers need to strategize and execute appropriate steering maneuvers promptly to avoid a traffic accident (McDonald et al., 2019; Petermeijer et al., 2016). The time-sensitive and complex takeover process presents a significant challenge for older adults, whose abilities to quickly perceive, process takeover requests and driving information, and execute necessary maneuvers are increasingly susceptible to normal age-related declines (Huang & Pitts, 2021, 2022b; Karthaus & Falkenstein, 2016; Bolslad, 2001). Especially, if drivers could have reduced situation awareness and divided attention which were commonly found when interacting with automated systems (Endsley, 1996); potentially leading to delayed takeover or failure to assume control in time to prevent a traffic accident (Müller et al., 2021).

Therefore, with an uprise in the older adult population, it may be critical to 1) understand whether older adults' situation awareness in automated vehicles is different compared to younger adults, and 2) develop and examine the effectiveness of human–machine interface (HMI) to support drivers (e.g., regain situation awareness), especially older adults, during a takeover.

1.1. Situation awareness

Situation awareness (SA) as defined by Endsley (1995), is an individual's understanding of their surrounding environment at any given moment, including their 1) perception, 2) comprehension, and 3) projection of both stationary and moving objects in their surrounding environment (Endsley, 1995). In the context of automated driving, SA plays a crucial role for drivers during a takeover event. Such that, at level one, perception, drivers must accurately perceive and identify takeover requests, as well as obstacles in their surroundings, such as road signs, signals, pedestrians, and vehicles. In level two, comprehension becomes essential as drivers must not only recognize the presence of objects but also comprehend their current states and intentions, allowing drivers to anticipate potential actions. Lastly, at level three, projection, the drivers' capacity to project the future movements of surrounding objects gains critical importance. During takeovers, understanding how these objects will navigate the environment is critical for making timely decisions and ensuring a seamless transition of control. Ultimately, these three levels of SA work in tandem to help drivers navigate takeover scenarios with precision and safety. In other words, with heightened SA in phase one of the takeover process, drivers can maintain a comprehensive understanding of their surroundings, road conditions, and the behavior of nearby vehicles, facilitating in phase two by helping to make informed decisions and precise control over the vehicle for safer takeover events. Drivers equipped with higher SA during a takeover event may be better equipped to adapt to potential hazards, sudden changes, and dynamic interactions, while executing takeovers with better precision and reducing the risk of accidents, enhancing overall road safety. Hence, SA serves as the cornerstone of the first phase and echoes throughout subsequent stages, ensuring a smoother and more efficient transition. Given this importance, there arises a need for a dependable and efficient human–machine interface (HMI) that can significantly regain or enhance situation awareness by promptly presenting vital environmental information, including the status and location of surrounding objects. Additionally, it can provide essential directional information, guiding drivers on maneuvering to avoid potential obstacles. This integrated approach may be able to support drivers throughout the entire takeover process.

1.2. Takeover requests (TORs)

Ultimately, the goal of a takeover request (TOR) is to ensure drivers are promptly and effectively informed about the need to take control, enhancing their situation awareness and response readiness during takeover events. TORs can be communicated in two different ways: unimodal and multimodal. In the unimodal approach, TORs are presented using a single sensory modality, which includes visual (V), auditory (A), or tactile (T) cues. For instance, a TOR might be solely visual, appearing on the vehicle's windshield

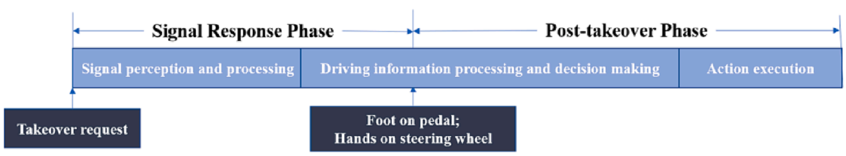

Fig. 1. The Takeover Model (Huang and Pitts, 2022b; adapted from Petermeijer et al., 2016).

or in-vehicle monitors through a visual display, or it could be purely auditory, conveyed through in-vehicle speakers as a sound, or even tactile, where a vibrotactile interface integrated into the driver's seat conveys the TOR (Geitner et al., 2019; Huang & Pitts, 2022b; Yun & Yang, 2020). On the other hand, in the multimodal approach, TORs are presented through a combination of sensory modalities, which creates a more attention-grabbing presentation. These combinations could involve any combination of visual (V), auditory (A), and tactile (T) cues (i.e., VA, VT, AT, VAT). Research has shown that multimodal displays are more effective than unimodal displays in eliciting faster reaction times (Geitner et al., 2019; Huang & Pitts, 2022b; Yun & Yang, 2020). For example, Geitner et al. (2019) used both unimodal (auditory, tactile) and multimodal displays (auditory and tactile) during an emergency brake event in an automated car and found faster reaction times, a reduced number of missed warning, and fewer false responses to brake events when using multimodal warnings compared to unimodal warnings. These results are in line with Multiple Resource Theory which proposes that humans have separate and limited cognitive resources for processing information from various sensory modalities or tasks. This theory suggests that optimal performance is achieved when different sensory channels or tasks tap into separate cognitive resources, preventing interference and enhancing efficiency (Wickens, 2008).

In terms of specific signal types, compared to visual and tactile displays, auditory displays have certain limitations, especially when used in isolation. Auditory channels can become overwhelmed in certain contexts, especially in environments where the background noises (e.g., engine sounds or road friction) or non-driving-related activities (e.g., listening to music or engaging in conversations) is persistently loud or complex, making it challenging to distinguish between critical takeover cues and background noise, regardless of volume adjustments or the temporary cessation of competing auditory activities (Huang and Pitts, 2022a). In contrast, multimodal displays leverage the advantages of various sensory channels, utilizing visual and tactile cues. This method is particularly effective in conveying takeover signals in noisy or intricate driving conditions, optimizing drivers' ability to promptly detect and process crucial information. This, in turn, elevates safety and situation awareness during takeover events. For example, multimodal displays, especially those incorporating tactile cues, are associated with quicker response times than those relying on a single display, and single auditory display was associated with longest response times (Huang & Pitts, 2022a,b).

However, most studies on this topic have focused on using multimodal warning signals in the first phase of takeover, for the warning purpose. It is unclear whether more meaningful TORs to indicate intricate maneuvers needed to evade potential traffic collisions, such as executing lane changes to avoid obstacles on the road or presenting the status or the location of other obstacles on the road, could be beneficial to the second phase of takeover process where more cognitive processing is needed.

1.3. Directional TORs

Previous research that focused on using a more meaningful HMI to instruct drivers on how to take over have utilized two types of displays: instructional (ipsilateral) and informative (contralateral) displays. An instructional display uses warning signals that direct drivers away from the potential hazard. On the other hand, an informative display instead directs drivers' attention towards the potential hazard (Cohen-Lazry et al., 2018, 2019). As an illustration, consider an instructional signal (arrow pointing left) displayed on the vehicle's windshield, or a vibrotactile sequential signal activated from the right side of the seat back and moving toward the left side, guiding the driver to transition into the left lane to prevent a potential collision with an adjacent vehicle in the right lane. Conversely, an informative signal exhibited on the left side of the windshield, or a vibrotactile sequential signal activated from the left side of the seat back and moving up toward the shoulders, notifies the driver of an imminent obstacle in the left lane. Consequently, the appropriate response involves steering away from the signal's direction and transitioning into the right lane.

Previous studies have examined the effects of instructional and informative signal types on takeover performance (Cohen-Lazry et al., 2019; de Winter et al., 2022; Huang & Pitts, 2022a,c; Straughn et al., 2009; Cohen-Lazry et al., 2018). For example, Huang and Pitts (2022a) used a multimodal display (VAT), utilizing all three modalities, with 24 participants aged 20–29 years of age. The study found that instructional signals showed a marginally significant benefit in takeover times compared to informative signals. On the contrary, in a separate study by Huang and Pitts (2022c), a multimodal display was not employed. Instead, they exclusively utilized the tactile modality, involving 40 participants aged 19 to 30 years of age. Interestingly, their findings indicated that only instructional signals led to longer takeover response times and higher maximum resulting acceleration in comparison to baseline signals, indicating a worse takeover performance.

Since these studies have only focused on comparing the effects of informative and instructional signals on the initial step of takeover (e.g., the perception and processing of takeover requests), the investigation into the effects of informative versus instructional signals on takeover events, particularly in the context of the later steps when drivers need to regain situation awareness and make timely decisions, remains underexplored within the domain of automated driving research. Another gap in existing research is the exploration of age-related differences in takeover events. It is recognized that older adults may encounter difficulties in maintaining situation awareness (SA) during takeovers, particularly impacting information processing and decision-making. However, empirical studies addressing this topic are limited. For example, one study, with participants aged 22 to 30, utilized eye-tracking technology to assess the influence of pre-takeover visual engagement tasks on SA during automated driving. This study found that prolonged observation of the driving scene correlated with a more balanced distribution of visual attention, improving overall SA, as measured by the Situation Awareness Global Assessment Technique (SAGAT) (Liang et al., 2021). It is important to note that this study exclusively involved younger adults. Therefore, conducting further research with older adults is crucial to gain a holistic understanding of the dynamics across varied age groups. Discerning potential disparities in SA levels between younger and older adults is vital, especially considering the growing demographic of older individuals who may increasingly use automated vehicles. This understanding is essential for comparing age-related SA level differences during takeovers. Additionally, research is limited on how multimodal displays, integrating visual and tactile cues, can bridge the SA gap between these age groups during takeovers.

1.4. The current study

This study aimed to investigate the effects of display (tactile, tactile and visual combined) and information presentation type (informative, and instructional), between age groups (older and younger adults), on automated vehicle takeover performance and situation awareness. We hypothesize that the implementation of multimodal displays utilizing instructional information will facilitate faster information processing (Cohen-Lazry et al., 2018, 2019) and higher levels of situation awareness (Huang & Pitts, 2022c; Martinez & Huang, 2022) for both younger and older adults, compared to other information types or tactile feedback alone. The research findings of this study can provide insights for the design of next-generation in-vehicle Human-Machine Interfaces (HMIs) that focus on enhancing the interaction between drivers and vehicles.

2. Methods

2.1. Participants

The study included 21 participants, that ranged between the ages of 18–76 (mean age = 43.9, standard deviation (SD) = 25.6), and consisted of ten older adults that ranged between 65 and 76 years of age (mean age = 69.9, standard deviation = 3.2) and eleven younger adults that ranged between 18 and 29 years of age (mean age = 20.3, standard deviation = 3.6). Participants were separated into the two age groups based on common definitions in a previous study of older adults (65+) and younger adults (18 years old up to 40) (e.g., Huang et al., 2022). All participants were self-reported active drivers. Based on their self-reported data, younger adults drove 3.2 days per week, while older adult drivers drove 5.2 days out of the week. The older adult participants were recruited from an associated program through San Jose State University's Center on Healthy Aging in Multicultural Population (CHAMP) and local senior centers. Younger adult participants were recruited from San Jose State University's Research Pool (SONA) system. Participants either received a $50 gift card or 2 hours of class credits as compensation for their time and participation. Inclusionary and exclusionary criteria for both groups included: 1) the requirement to have a valid driver's license, 2) normal or corrected-to-normal vision, and 3) have no cognitive or neurological impairments, as well as 4) no self-reported susceptibility to motion sickness. This study was approved by San Jose State University's Institutional Review Board (IRB Protocol ID: 21278).

2.2. Apparatus/Stimulus

2.2.1. MiniSim driving simulator and tactile seat

This experiment employed a fixed-based medium fidelity driving simulator, developed by the University of Iowa Driving Safety Research Institute (DSRI), named miniSim, see Fig. 2. The miniSim system incorporated three 48-inch LED monitors to display the simulated driving environment. In addition, there was a single 24-inch LCD screen integrated into the dash that simulated the in-vehicle odometer. This also included a steering wheel equipped with turn signals, foot pedals (i.e., gas, brake), and a standard-sized adjustable leather seat. To start the vehicle there was a push-to-start button on the dash, along with other buttons to simulate a vehicle's dashboard (i.e., emergency lights, high and low beam buttons, buttons to adjust the mirrors). Also included was a tactile seat, which provided vibrations to convey spatial information, such as the presence of obstacles, or directional information, such as indicating the safest available lane.

2.2.1.1. Meaningful signals. As shown in Fig. 3, the visual signals (V) were presented in a 200 × 200-pixel format, featuring either red

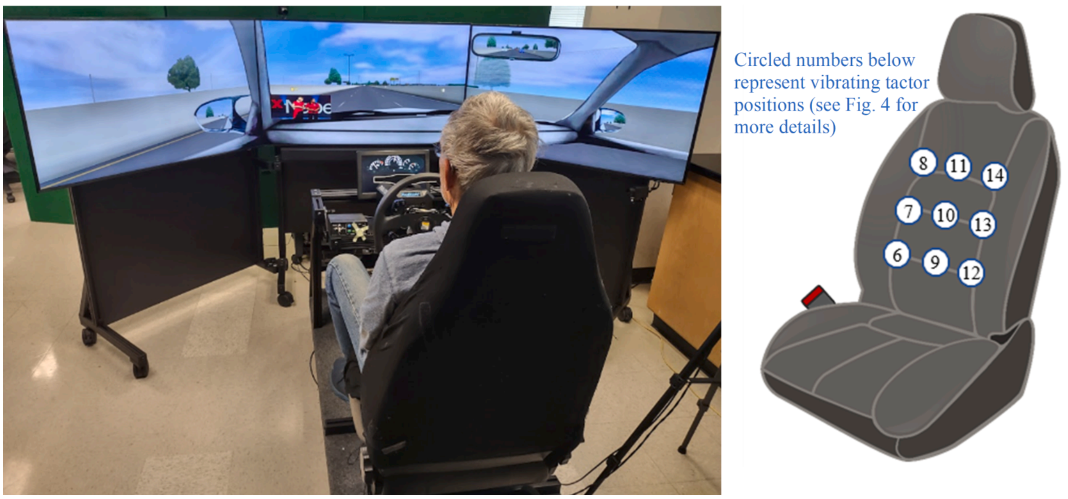

Fig. 2. The miniSim driving simulator and the tactile seat.

and orange squares (informative), green arrows (instructional), or a red circle (baseline), positioned above the odometer in the center of the screen. For example, visual informative signals informed drivers of surrounding obstacles in the environment, such as vehicles, with red (forward collisions) and orange squares (vehicles on left or right sides) highlighting the obstacles depending on their position. In the case of a forward collision a red (impeding danger) square would appear on the windshield highlighting the obstacle in front. However, an orange (warning) square would also appear on the rearview mirror, indicating to the driver from which side a vehicle was approaching. Instructional signals, on the other hand, provided the driver with guidance on how to maneuver their vehicle to avoid a potential traffic collision, using a green arrow (instruction). For example, if the left lane was deemed the safest option due to the absence of vehicles, a green arrow pointing to the left would be displayed on the windshield. Lastly, the baseline condition displayed a red circle on the screen, not implying any additional information other than to prepare to take over control of the vehicle.

Tactile (T) warning signals were presented using nine 1″ x 0.5″ x 0.25″ piezo-buzzers (called C-2 tactors, developed by the Engineering Acoustics, Inc.) attached to the seat back in a 3x3 array (Chiossi et al., 2022; Telpaz et al., 2015), as seen Fig. 2. The tactors emitted vibrations at a frequency rate of 250 Hz. Examples of these tactile vibration patterns can be observed in Table 1. Instructional signals included navigational (left turn, right turn) signals, while informative signals included surrounding vehicle locations and moving directions (left side, right side). The signal patterns and durations used in this study were developed from a previous study which were reviewed and tested during an in-lab study without the actual driving task (Martinez and Huang, 2022). Similar to the visual signals, tactile instructional signals helped to guide drivers towards the safest lane by vibrating from either right-to-left or left-to-right on the lower back twice, indicating which lane was most available. Informative signals vibrated starting on the lower back and moved up towards the head on either the left- or right-hand side depending on which side the vehicle was approaching from. Examples of these tactile vibration patterns can be observed in Fig. 4. As a point of comparison, a baseline condition was implemented where no additional information was provided, apart from a warning signal indicating that something has happened in the driving environment, indicated by all the tactors vibrating at the same time. In the visual and tactile (VT) condition both signals were presented at the same time.

2.3. Driving scenario

Participants rode through a simulated SAE Level 3 automated driving scenario, where the vehicle controlled both the lateral and longitudinal deviation. The automated vehicle travelled in the middle lane at 65 mph. At any given moment there was a leading vehicle 7-seconds ahead of the subject vehicle (Eriksson & Stanton, 2017; Huang & Pitts, 2022a). In addition, two fleets of vehicles were also traveling at a constant 150 feet away at 65 mph followed the subject vehicle on both the left- and right-hand lanes. Intermittently, a construction zone would appear in the center lane in front of the subject vehicle causing the lead vehicle to suddenly have to stop. In turn, this led to the subject vehicle detecting the obstacle and potential forward collision threat 667 ft ahead (a 7-second lead time to forward collision) causing the initiation of a takeover request (TOR). Concurrently, the two fleet of cars following behind alternated

Fig. 3. Example of visual signals used in the study.

Table 1
A Summary of Tactile Signals and Patterns Used in the Study.

Takeover request	Tactor Sequence
Instructional	
Drive into the left lane	6 -> 9 -> 12
Drive into the right lane	12 -> 9 -> 6
Informative	
Back Left	12 -> 13 -> 14
Back Right	6 -> 7 -> 8
Baseline	
(Prepare to take over)	All tactors vibrating together

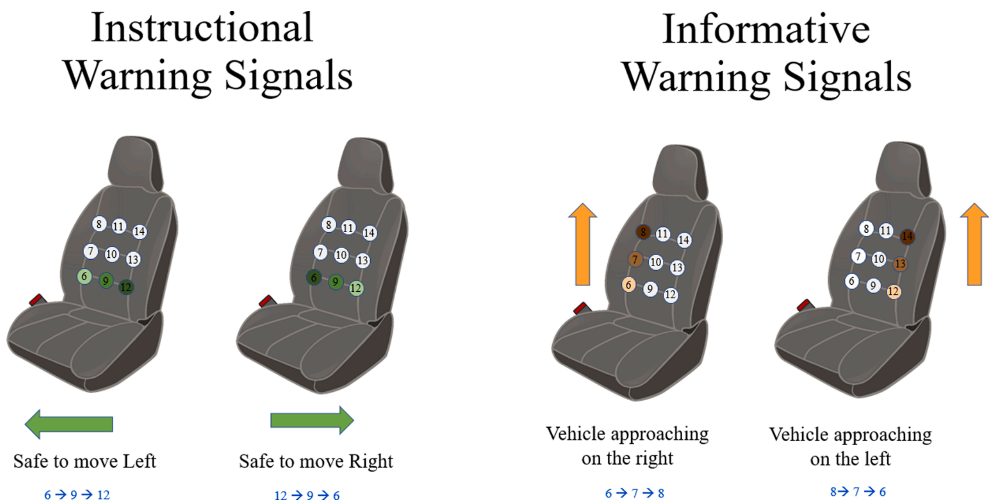

Fig. 4. Example Pattern Descriptions for Tactile Signals.

randomly get closer to the subject vehicle, 40 ft away, to close off that lane to the subject vehicle and cause further complexity to the driving task, leading to the driver needing make for a decision of "which lane is safest to maneuver into?" as needing to take into consideration any potential rear-end collisions with these vehicles. After processing the TOR, either in signal tactile or combined visual and tactile formats, and the driving environment, drivers needed to move their hands and feet back to the driving position and press on the brakes to deactivate the TOR and attempt to carry out their driving maneuver into the safest lane. However, no actual takeover was necessary. At this point the screen would black out, the driving scenario paused, and SAGAT would be queried (Liang et al., 2021). SAGAT, or Situation Awareness Global Assessment Technique, is a method used to evaluate a driver's situation awareness (SA) in a driving scenario. It involves presenting drivers with various scenarios or tasks, then assessing their ability to perceive, comprehend, and project information about their surroundings, such as other vehicles, road signs/signals, and potential hazards. After the 3-question query gauging perception, comprehension, and projection was complete, the participant pressed the start button on the dash to continue the simulation.

2.4. Procedure

Upon arrival at the lab, participants were greeted and given an overview of the experimental process. Subsequently, they were asked to sign the consent form if they agreed to participate. In addition, participants were asked to fill out a pre-experiment questionnaire, which obtained demographic information and driving experiences. To begin the study, participants were seated in the miniSim and familiarized with the driving equipment, environment, and the takeover requests. To ensure participants perceived the tactile stimuli correctly, participants underwent a 5-minute training period prior to the start of the actual experiment, where they practiced takeover procedures. After successfully interpreting all tactile patterns, participants moved on into the experiment, each participant completed a total of three randomized drives, one for each information type (i.e., informative, instructional, and baseline). Within each drive, a total of 1–2 takeover requests were presented and then randomly repeated, based on specific conditions. For example, in the instructional/informative conditions, two takeover request types (i.e., V, VT) were randomly applied (each signal type was repeated two times), while in the baseline condition, only one takeover request was presented and was also repeated two times. In total, participants encountered ten takeover requests throughout the study (i.e., four V, four VT, and two baseline), however, no actual takeover action was necessary. The average time interval between each takeover request was approximately 2-minutes. Between this time participants were instructed to focus their attention on a non-driving-related-task (NDRT), which was presented to participants on the bottom of the main screen on either the left or right side, to prevent any order effects this was counterbalanced. The NDRT included watching a video of a TED talk, which was played to control for driver's attention allocation not allowing them to prepare for TOR in advance, simulating potential real-life scenarios that may occur during automated driving. To ensure participants focused their attention on the NDRT, they were told there would be a quiz at the end of the study to gauge how well they were paying attention to the videos, a method learned from previous studies (e.g., Huang and Pitts, 2022c). The video was paused during a takeover, and upon reactivation of the automation by participants, it resumed. At random intervals during the drive, when the driving scene became more complex, such as at a construction zone with approaching vehicles that overwhelm the system and render it unable to handle the driving task, a takeover request was presented to the participant. The driver was then faced with the challenging decision of determining the safest lane to maneuver into, in order to avoid an accident.

To aid the driver in making this decision, a meaningful signal pattern was presented in either, or both, a visual and tactile modality using informative or instructional warning signals, as described in Section 2.2.2. Once the driver had processed the TOR and began to become aware of their environment, while deciding which lane was safest to maneuver into, they then needed to move their hands and feet back (i.e., tap on the brake in this study) into the driving position. This action disengages the automated system, returning control of the vehicle to the driver. Once the automated system was disengaged, the screen went dark, and a survey SAGAT (Endsley, 1995; Wang et al., 2022) was presented on a tablet to measure SA. The questions presented to participants were coded to gauge the perception, comprehension, and projection awareness of the participant after each takeover event. All levels of awareness were asked during each drive. Following the completion of each block there was a 5-minute break. To prevent potential order effects, the presentation of the three drives were counterbalanced for each participant and lasted approximately 15 min. Upon completion of all three blocks, the participant completed the post questionnaire, was debriefed, compensated, and asked to sign for their compensation, marking the end of the experiment. Overall, the study lasted approximately 90 min and was split into three sections to help prevent fatigue, as shown in Table 2 below.

2.5. Dependent measures

Both subjective and objective measures were taken into consideration in this experiment. Objective measures included takeover performance: processing time and situation awareness. Subjective measures included pre- and post-questionnaires that gathered information about the participants demographic information, driving experience, as well as attitudes and opinions of the HMI.

2.5.1. Information processing time

Information processing time was measured in seconds (s). This refers to the duration between the initiation of the TOR and the moment when participants became aware of their environment and physically pressing on the brake pedal with their foot. This metric was used to determine how quickly drivers could perceive and process takeover requests, while making the appropriate decision to avoid a possible traffic collision.

2.5.2. Situation awareness

A total of ten queries were administered, with each query comprising three distinct questions corresponding to different levels of SA: perception, comprehension, and projection. Each question had only one right answer, allowing for the calculation of total scores for each query (range from 0 to 3). For instance, in the context of level one (perception), participants were presented with a question such as "What was the color of the car ahead of you?" Transitioning to level two (comprehension), the question asked was "From which side was the closest car behind you approaching?" Finally, for level three (projection), participants were prompted to complete the statement: "My vehicle is going to:", based on their projection of how the vehicle's automated system was going to maneuver to avoid the accident.

2.5.3. Subjective Pre/Post questionnaire

In order to explore how drivers' perceptions of TOR signals might impact takeover performance, a qualitative method was utilized to evaluate subjective viewpoints regarding the various signal types. First, participants were given a pre-questionnaire at the beginning of the experiment to collect information on demographics and driving experience. At the end of the experiment, participants were given a post questionnaire that included a technology acceptance questionnaire and preference-related questions, such as preferred information types. This included a nine item 5-point Likert scale (with five items for usefulness and four items for satisfaction), ranging from −2 to 2, designed to gain insights into participants' subjective attitudes, experiences, and opinions concerning the design of the

Table 2
Overview of Procedures.

Pre-Questionnaire & Overview	25 min
Signals Practice	5 min
Drive 1	15 min
Break	5 min
Drive 2	15 min
Break	5 min
Drive 3	15 min
Post-Questionnaire & De-brief	5 min
Approximate Total: 90 min	

Human-Machine Interface (HMI), regarding its usefulness and satisfaction towards the takeover requests' signal information types and modality (Huang & Pitts, 2022a).

2.6. Data analysis

A 2 (Display type: Tactile, Visual and Tactile) x 3 (Information type: Instructional, Informative, Baseline) x 2 (Age: Younger, and Older adults) mixed methods design was used in this study. Here, independent variables include age (between-subject), display (within-subject), and information type (within-subject). Data were analyzed using a three-way mixed analysis of variance (ANOVA) to compare differences between displays, information type, and age groups in the ability to effectively improve driver's situation awareness and information processing time during a takeover event. Results were considered statistically significant where $p < 0.05$. Partial eta squared (η_p^2) was used to measure effect size. For violations of sphericity tests and degrees of freedom corrections Greenhouse-Geisser estimates were applied. To identify significant differences and interactions between the various levels Bonferroni corrections were applied for multiple comparisons Post Hoc analysis. The statistical analysis was conducted using IBM SPSS Statistics 28.0.

3. Results

3.1. Processing time

There was a significant main effect of display ($F(1, 19) = 10.619$, $p = .004$, $\eta_p^2 = 0.359$) and a marginal main effect of information type ($F(2, 38) = 2.572$, $p = .090$, $\eta_p^2 = 0.119$) on processing time (Fig. 5). Specifically, the VT display had a shorter processing time (mean (M) = 4.121 seconds, standard error of mean (SEM) = 0.159), compared to the T display (M = 4.396 s, SEM = 0.130). Post hoc analysis also revealed that no difference was found between the informative information type (M = 4.164 s, SEM = 0.151) and the baseline (M = 4.183 s, SEM = 0.170), and the informative information type was marginally shorter than the instructional information type (M = 4.429 s, SEM = 0.153, $p = .080$). There was also a main effect of age on processing time ($F(1, 19) = 8.732$, $p = .008$, $\eta_p^2 = 0.315$). Younger adults (M = 3.848 s, SEM = 0.192) were shown to have faster processing times compared to older adults (M = 4.669 s, SEM = 0.201).

There was also a significant interaction effect between display and information type ($F(2, 38) = 4.147$, $p = .023$, $\eta_p^2 = 0.179$). Specifically, the VT display (M = 3.843 s, SEM = 0.216) had shorter processing times when the information type was informative

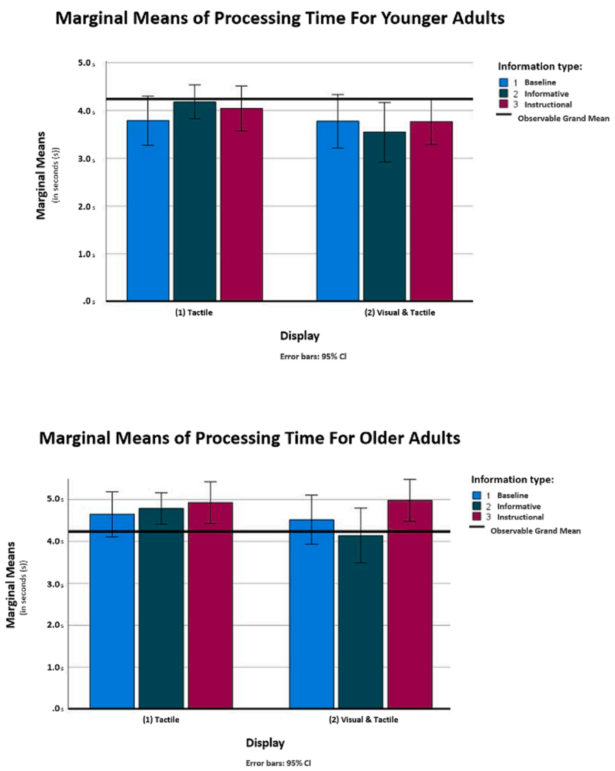

Fig. 5. Marginal Means of Processing Time by Display, Information Type, and Age Group.

compared to the tactile display alone (M = 4.484 s, SEM = 0.123, p =.002), but no differences were found between the two displays in the baseline condition (T: M = 4.219 s, SEM = 0.178; VT: M = 4.146 s, SEM = 0.194; p =.633) or the instructional information type (T: M = 4.485 s, SEM = 0.163; VT: M = 4.373 s, SEM = 0.165; p =.366).

3.2. Situation awareness (SAGAT)

There was a significant main effect of information type on situation awareness (F (2, 38) = 4.963, p =.012, $\eta_p^2 = 0.207$) in both younger and older adults (Fig. 6). Specifically, the analysis showed informative information type (M = 2.215, SEM = 0.111) yielded the highest situation awareness compared to instructional (M = 2.002, SEM = 0.113) and baseline (M = 1.866, SEM = 0.111) conditions. However, no significant differences were found between younger (M = 1.947, SEM = 0.126) and older (M = 2.108, SEM = 0.132) adults, as well as between the VT (M = 2.028, SEM = 0.085) and T (M = 2.027, SEM = 0.115) displays in relation to SAGAT scores (F (1, 19) = 0.786, p =.386, $\eta_p^2 = 0.040$, and F (1, 19) < 0.001, p =.993, $\eta_p^2 < 0.001$, respectively).

There was also a significant interaction effect between display and information type (F (2, 38) = 43.180, p = <0.001, $\eta_p^2 = 0.694$). Specifically, in the baseline, single T (M = 2.336, SEM = 0.147) had a higher SAGAT score compared to the display type VT (M = 1.395, SEM = 0.112, p <.001). However, with both informative (T: M = 2.050, SEM = 0.136; VT: M = 2.380, SEM = 0.117, p =.015) and instructional (T: M = 1.695, SEM = 0.146; VT: M = 2.309, SEM = 0.120, p <.001) information types, the SAGAT scores for single T were lower than for VT.

3.3. Post subjective experiences assessment

No significant main effects of display (usefulness: F (1, 19) = 0.272, p =.608, $\eta_p^2 = 0.014$; satisfaction: F (1, 19) = 0.108, p =.746, $\eta_p^2 = 0.006$), information type (usefulness: F (2, 38) = 0.603, p =.552, $\eta_p^2 = 0.031$; satisfaction: F (2, 38) = 0.290, p =.750, $\eta_p^2 = 0.015$), or age (usefulness: F (1, 19) = 0.024, p =.878, $\eta_p^2 = 0.001$; satisfaction: F (1, 19) = 0.760, p =.394, $\eta_p^2 = 0.038$) on usefulness and satisfaction were found.

Fig. 7 illustrates evidence supporting participants' preference for in-vehicle warning signals to present the location of other vehicles and/or obstacles, as opposed to receiving instructions on how to control their vehicle. Specifically, 12 out of 21 participants (57%) expressed a clear preference for in-vehicle warning signals to warn them of the "location of other vehicles/obstacles" in their driving environment. In contrast, only 2 out of 21 participants (9.52%) preferred in-vehicle warning signals presenting "instructions on how to control the vehicle." These findings align closely with the objective outcomes of the research study, demonstrating participants'

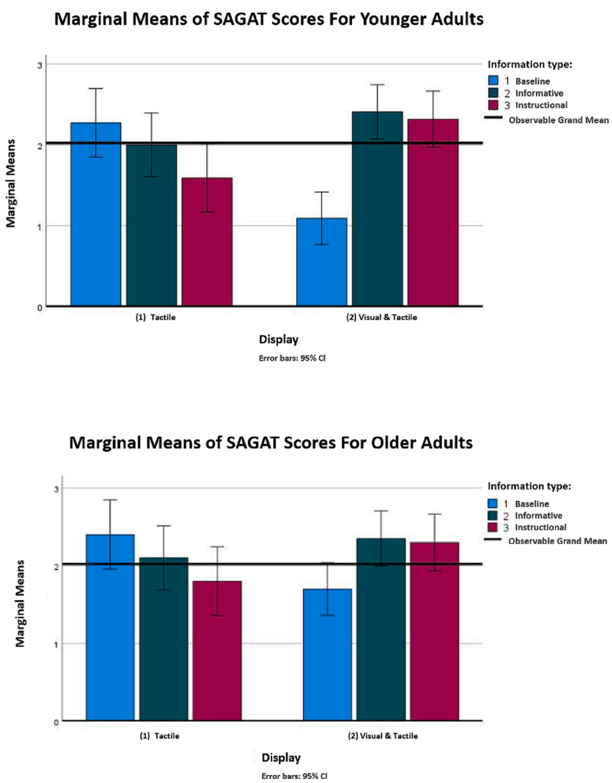

Fig. 6. Marginal Means of SAGAT Scores by Display, Information Type, and Age Group.

inclination towards informative warning signals.

4. Discussion

This study investigated the effects of display (tactile, tactile and visual combined) and information presentation type (baseline, informative, and instructional) on automated vehicle takeover performance (information processing time and situation awareness). Overall, the utilization of informative signals were associated with faster information processing time and higher situation awareness compared to the instructional information type. Additionally, multimodal displays, i.e., VT, were related to faster processing speed compared to the single tactile display, but no main effect of the display was found on situation awareness. Similarly, no age-related difference was found in situation awareness, but older adults presented slower information processing times compared to younger adults.

4.1. Informative vs. Instructional information type

The results found in this study indicate that the informative information type had faster information processing times and higher situation awareness levels. This further supports the previous findings in Huang and Pitts (2022c) who found that instructional signals were associated with worse takeover performance compared to baseline, but no difference was found between the informative and baseline signals. A possible explanation for this finding may be that the informative information type, which provides information about the location and status of surrounding vehicles in the environment, aided drivers in building a heightened level of situation awareness (Endsley, 1995) and faster information processing. Conversely, instructional signals directed drivers to follow the system's guidance for maneuvers without requiring them to understand the driving environment. Consequently, without additional information about the surroundings, drivers may have carried out post-takeover tasks with increased uncertainty regarding the positions of surrounding vehicles and the accuracy of their maneuvering decisions. This hypothesis gains further substantiation from the subjective measures detailed in Section 3.3, indicating that drivers showed a preference for in-vehicle warning signals that conveyed the location of other vehicles and potential obstacles, as opposed to receiving instructions on vehicle control. Future studies may also examine the effects of trust level in the two information types given that a higher trust level in the informative information type than in the instructional information type may also result in similar results.

4.2. Multimodal vs. Unimodal displays

This study also revealed a shorter mean difference in processing time when using multimodal displays compared to unimodal displays relying solely on tactile feedback. This result aligns with prior research indicating that multimodal signals are linked to quicker response times than unimodal signals (e.g., Geitner et al., 2019; Yun & Yang, 2020). It underscores the benefits of multimodal displays, which are not only superior as warning signals but are also effective for takeover assistance, especially during the later stages of takeovers where rapid processing of driving environment information is crucial. Moreover, the presence of both informative and instructional information types elevated levels of situation awareness above the baseline, a trend absents with the exclusive use of single tactile display. This could be due to the redundancy in information provided by multimodal displays, enhancing the chances of noticing and understanding critical information, such as an impending vehicle collision. This observation strengthens the argument that incorporating multimodal displays especially the visual and tactile components is advantageous when the displays are meaningful, either instructional or informative.

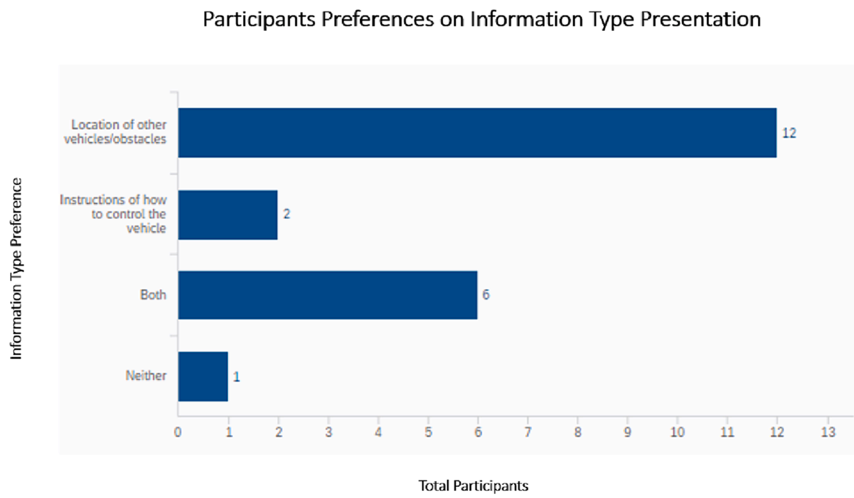

Fig. 7. Frequency of participants' choices in selecting a warning signal preferenceCFAQWSP.

4.3. Younger vs. Older adults

Another interesting finding from the study was the absence of any age-related difference in situation awareness. This implies that, during the takeover, older adults were equally proficient as their younger counterparts in assessing the driving environment. One plausible explanation for this could be the extensive driving experience of older adults. This experience might enable them to employ effective strategies to consistently gather information from the driving environment, even during automated driving when engaged in non-driving-related tasks. This hypothesis gains support from studies such as Huang and Pitts (2022b), where older adults were observed (by an eye tracker) to check the driving environment more frequently while watching a video during automated driving. Subjective reports from older adults also revealed older adults' strategies during the automated driving that they would prioritize monitoring the driving environment even though they were instructed to watch a video (Huang & Pitts, 2020), highlighting their proactive approach to maintaining situation awareness. Additionally, younger adults exhibited shorter information processing time compared to older adults, aligning with previous studies (e.g., Huang and Pitts, 2022b). A potential explanation for this discrepancy in processing speed between age groups might be attributed to general age-related declines in sensory perception, psychomotor skills, and cognitive abilities. As individuals age, they often experience a deterioration in sensory perception, affecting the efficiency of information intake, and a decline in psychomotor skills, impacting their speed to step on the brake after perceiving the takeover requests. Moreover, cognitive abilities, including processing speed, working memory, and attention, are known to decline with age, contributing to the observed disparities in information processing times between the younger and older adults. In summary, these age-related declines might collectively lead to the observed discrepancy in information processing times, as older individuals may face challenges in efficiently processing information due to these age-related declines.

5. Limitations

Limitations of the study included the challenge in ensuring similar cognitive and physical abilities among older adults, due to the non-homogeneous nature of aging. Such that, even individuals of the same chronological age can exhibit varying cognitive and physical capabilities, consequently affecting their takeover performance and situation awareness. Future studies might want to consider grouping older adults based on their non-chronological age factors (individual cognitive or physical abilities) rather than relying solely on chronological age as a grouping criterion. Furthermore, our study exclusively examined a single driving environment, a 3-lane highway. However, it is important to note that urban areas typically present a higher level of complexity, potentially leading to more frequent takeover events. Future research may benefit from diversifying driving scenarios to gain a deeper understanding of takeover events, particularly in urban settings. Additionally, this study focused solely on one type of takeover event, specifically construction zones. To enhance the ecological validity of findings, future studies should incorporate a greater variety of takeover events. This can involve introducing different environmental factors, such as varying weather conditions and road types, to capture a more comprehensive understanding of drivers' responses in diverse driving conditions. Lastly, it is worth noting that SAGAT is an intrusive measurement tool, which necessitates pausing the simulated driving scenario to capture data, which might not accurately represent real automated driving experiences. Future studies may want to focus on utilizing only physiological measures to assess SA, which could eliminate the need for scenario interruptions. This approach would enable the measurement of post-takeover driving performance differences between younger and older adults in a more naturalistic setting (e.g., Zhang et al., 2023).

6. Conclusion

This study investigated the effects of display (tactile, combined tactile and visual) and information presentation type (baseline, informative, and instructional) on the takeover performance (information processing time and situation awareness) of automated vehicle takeovers. Findings include informative signals were associated with faster information processing times and higher situation awareness than the instructional information type. Furthermore, multimodal displays, i.e., the tactile and visual combinations, were related to faster processing speeds compared to using tactile displays alone. However, there was no significant difference in situation awareness levels across different displays. Similarly, no age-related differences were observed in situation awareness levels, but younger adults exhibited faster information processing times in contrast to older adults. These findings may help to inform the design of human–machine interfaces for next-generation vehicles and guide automotive manufacturers in determining the most appropriate takeover signal type and pattern, and information type across age groups.

CRediT authorship contribution statement

Kimberly D. Martinez: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Gaojian Huang:** Supervision, Resources, Project administration, Funding acquisition, Conceptualization, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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