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Research on Multimodal Human-Machine Interface for Takeover Request of Automated Vehicles

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ABSTRACT
In L3 automated driving, the driver performing the non-driving related tasks (NDRT) is easy to miss the takeover request and cause safety hazards. The takeover prompt strategy has a great impact on this situation. In this paper, four multi-modal takeover interfaces for automatic driving are designed to address the typical takeover scenarios in which the driver is under medium and high-level task loads. The driving simulator is used to conduct experiments, and each scheme's takeover success rate, takeover time and takeover quality are selected as the evaluation criteria to study the effect of different interfaces on the driver's takeover performance. The results show that the multimodal takeover interface can shorten takeover time, and the visual-auditory-tactile prompt has the shortest takeover time; and the visual-auditory prompt and auditory-tactile prompt have nearly the same takeover time, but the latter increases the longitudinal deceleration of the vehicle; the visual-tactile prompt has the worst takeover performance. These results provide practical implications for developing suitable interfaces to remind drivers to take over the automated vehicles.

KEYWORDS
human machine interface; takeover in driving automation; non-driving related tasks; takeover performance.

1. INTRODUCTION

With the rapid development of driving automation technologies, level 3 automated vehicles have progressively reached mass production. According to the Society of Automotive Engineers (SAE) definition of automation level 3, due to the imperfections in the capabilities of driving automation systems, while these systems continuously perform all driving tasks under their designed operating conditions, drivers are required to take over the vehicle and switch to manual driving when necessary [1].

Vehicles with level 3 or higher automated driving capabilities can partially liberate drivers' limbs and attention, leading to engagement in NDRTs (non-driving related tasks), which would result in driver distraction. Research on multiple resource theory suggests that common NDRTs primarily occupy drivers' visual, auditory or motor capabilities [2]. The processing of takeover information involves perception, cognition and decision-making, eventually leading to takeover actions. This process can impose a significant cognitive load on the driver. Factors affecting driver takeover performance include the state of distraction [3], passive fatigue [4], mind-wandering [5], traffic conditions [6], driver's age [7], emotional valence and arousal [8], and the time budget for takeover [9].

Numerous scholars have researched takeover, which is a critically important activity in driving. In studies concerning the timing of takeover prompts, reference [10] found that drivers could take control of the vehicle within 4-8 seconds, depending on the complexity of the takeover situation. Research by Gold et al. [11] shows that shorter takeover times are associated with quicker decision-making and reactions by drivers, but the quality of takeover is generally poorer. Reference [12] concluded from their experiments that 6 seconds is the balance between shorter reaction times and higher quality of takeover. If the TOR (takeover request) time needs to be reduced in designs for acute threats, a duration of no less than 6 seconds would be preferable.

Most studies have focused on the effectiveness and efficiency of mono-modality takeover prompt, with fewer exploring the effectiveness and differences of multimodal takeover prompt strategies. This study primarily investigates the impact of multimodal takeover prompts on takeover performance and proposes corresponding prompt strategies to enhance the success rate and experience of takeover. The research study the impact of four different combinations of takeover prompt strategies on driver performance under NDRT loads. The results can provide theoretical fundamentals for the design of driving automation takeover prompts.

The next section will review drivers' situation awareness of in-vehicle HMI (human machine interfaces), NDRTs, takeover stratification strategies and related HMI studies. Section 3 primarily introduces the experimental equipment and details of the participants. Sections 3.1 and 3.2 mainly introduce the takeover tasks and NDRTs in the experiment, while 3.3 and 3.4 describe the design of multimodal prompts and the experimental procedure. Section 3.5 discusses how experimental data are processed. Sections 4 and 5 specifically analyse and discuss the experimental results and conclusions.

2. LITERATURE REVIEW

2.1 Situation awareness

Situation awareness (SA) involves the perception of environmental elements within a specific time and space. Reference [13] categorised situation awareness within dynamic systems into three levels: perception (level 1), comprehension (level 2) and projection (level 3). When drivers fail to understand the current situation during takeover, their performance in responding to takeover requests (TORs) decreases, thus increasing the risk of accidents [14].

Situation awareness is a dynamic and continuous process. Upon receiving a TOR, drivers need to immediately shift their attention from NDRTs to safely controlling the vehicle under the current road and traffic conditions. Within the given takeover time, they must complete information gathering, environment evaluation and decision-making to achieve full control of the vehicle [6]. According to Kim et al. [15] when drivers have higher situation awareness capabilities, the time required to recognise and respond to the TOR is reduced, enabling quicker reaction to potential hazards during takeover. Reference [16] reviewed how in-vehicle human-machine interfaces (HMI) can enhance drivers' situation awareness at different levels. Besides, incorporating explainable AI (XAI) in HMI, informing the driver of the situation and why they need to take over appropriately can make such situations more transparent and explicit for drivers, preventing potential risks.

2.2 NDRTs

A narrative review by de Winter et al. [18] indicated that as the level of automation increases, drivers are more inclined to engage in non-driving related tasks (NDRTs) during conditional automated driving. Reference [6] pointed out that engagement in NDRTs can lead to reduced attention to the road environment, thereby degrading takeover performance. When NDRTs overlap in resource demands with driving tasks, it results in a more significant decline in takeover performance [19]. Additionally, low mental workload causing drowsiness also leads to a decrease in performance. This aligns with research indicating that driving performance in automated driving is related to the psychological workload level involved in NDRTs, both excessively high or low psychological workloads can impair driving performance, especially lateral control [2].

A survey identified daydreaming, writing text messages, eating and drinking, browsing the internet and making phone calls as the anticipated types of NDRTs by drivers [20]. Based on this, [21] selected work, entertainment and rest as three categories of NDRTs to study their impact on drivers' manual driving performance following a TOR. The results showed that driving performance was significantly impaired after engaging in any of the three types of NDRTs, with NDRTs as brief as five minutes capable of impairing driving performance following a takeover. A study explored the behaviour of drivers engaged in NDRTs under different levels of automation, finding that increased engagement in NDRTs may reflect both positive consequences of vehicle automation, such as enhanced subjective safety and decreased workload, and negative consequences, such as reduced situation awareness [22].

2.3 Interfaces for takeover requests

Visual tasks have the most significant impact on participants' mental workload, with most information collected through visual perception modalities entering visual cognition [23]. The mean takeover time (TOT) for purely visual TORs is longer than for auditory or vibrotactile TORs [24]. Research suggests that visual-only warnings are not suitable as TORs, as drivers engaged in driving NDRTs are likely to ignore visual signals and not interpret them as urgent, and instead, they should be combined with other channels to provide takeover information [24, 25]. Various approaches have combined auditory and tactile channels, conveying critical additional semantic information through auditory feedback with varying degrees of urgency and repetition or tactile feedback with different amplitudes and frequencies [26, 27]. Reference [28] indicates that transmitting additional information in these forms during the TOR process can shorten takeover times. Using auditory voice broadcasts to inform drivers of the current vehicle status results in drivers reacting more quickly and confidently to TORs, while also perceiving a reduced workload [29]. Another study examined the correct response rate and reaction time under static and dynamic vibration takeover prompts from the driver's seat vibration motor, showing that vibrotactile stimuli presented through the driver's seat as warnings are effective, with static vibration TORs prompting quicker driver takeover than dynamic patterns [30].

Multimodal displays, which combine two or more sensory modalities, can output more information per unit of time compared to unimodal displays, thus resulting in better task performance [31]. Displays combining all three modalities (i.e. visual, auditory and vibrotactile) are rare in automotive driving, with more traditional unimodal visual or auditory warnings being common [32]. In a survey, five different urgency scenarios were proposed (highway exit, lane change, construction work, automation failure and traffic accidents ahead), with the multimodal combination of auditory, visual and vibrotactile messages being the preferred option for supporting TORs in high urgency situations [33]. Furthermore, differences in the effectiveness of multimodal warnings in past research can be explained by whether they are semantically, temporally and spatially congruent, leading to redundancy [34, 35].

2.4 Takeover strategies

Reference [36] highlighted the importance of understanding drivers' predetermined takeover strategies for enhancing situation awareness and safety in driving automation. Their research identified eight strategic approaches for managing attention and executing takeovers, employing multi-stage TORs to reduce the likelihood of alternating attention between non-driving activities and the road, and to shorten the duration of takeover preparation, thereby optimising the takeover actions of advanced drivers. Research has examined the strategy choices of drivers when faced with TORs from automated vehicles, from the perspective of interruption management. Their findings suggest that the driving environment, the level of trust in the automation system and the type of auditory cues significantly influence drivers' strategic choices [37]. The application of interruption management theory helps to further understand drivers' takeover behaviours. A study tested the viability of hierarchical takeover warnings and gamified incentive strategies. The results indicated that the hierarchy of takeover alerts did not significantly affect takeover performance but did enhance user experience. Meanwhile, gamified strategies met users' emotional and personalisation needs, beneficially impacting user experience [38]. An experimental research on different types of verbal takeover prompts investigated independent variables including speech rate, intonation and emotion, demonstrated that a faster speech rate and certain takeover phrases can create a sense of urgency in takeover situations, whereas the gender of the participant and emotional tone had little impact on takeover performance [39].

3. METHODOLOGY

3.1 Experimental equipment

The experiment was conducted on a driving simulator, as shown in *Figure 1*. The driving scenario design software used was UC-Win/Road, which is capable of simulating traffic flow, road vehicles, traffic signals and pedestrian traffic. This software was utilised to construct experimental scenes that meet the requirements for human-machine interaction studies in driving automation and can synchronously collect data on vehicle speed, braking coefficients, etc., with a data collection frequency set at 20 Hz. The experimental hardware included: a Logitech G29 steering wheel and accelerator-brake pedal kit, a Microsoft Surface tablet (positioned behind the steering wheel to simulate a full LCD dashboard interface), a Canon 750D camera (used to record the full process of participant takeover during the experiment), an iPhone 11 (to play task videos) and a mobile phone holder. The tactile prompt is generated by a back cushion with a utility of vibrating massage. The cushion is placed on the seat's sitting surface against the backrest to simulate the common electric car seat with a vibration massage function. The vibration rate is 600 times per minute, which is slightly higher than the common electric car seat.

Figure 1 – Environment and apparatus for driving experiment

3.2 Participants

A total of 30 participants (18 males and 12 females) were recruited for the experiment, with ages between 18 and 50 years old (M=29.4 yrs, SD=8.8 yrs) and driving experience ranging from 1 to 10 years (M=3.4 years, SD=5.2 years). All participants had normal or corrected-to-normal vision and were somewhat familiar with driving automation technology. Before invitation, each participant was asked two questions by phone to ensure him/her was in good physical condition, free from fatigue or alcohol influence. The questions are "How many hours did you sleep last night?" and "Have you consumed alcohol in the past 24 hours?" Participants who slept less than 8 hours in the previous night or answered YES to the second question would not be invited to participate in the experiment. The experiment is arranged in the late morning (9:30-12:00) or early afternoon (14:00-16:30). In the process, when signs of fatigue are noticed, such as yawning, difficulty concentrating and slumping posture, the experiment would be paused and the participant is asked to take a break. The experiment continued after the participant regained their energy.

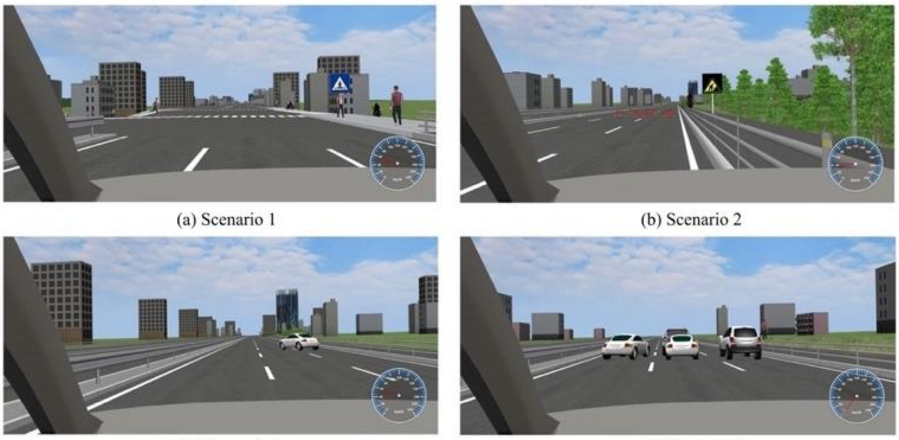
3.3 NDRTs and takeover scenarios

Common NDRTs include chatting, listening to music, browsing images and text and watching videos. This paper classifies NDRT that occupy two or more of the visual, auditory and tactile channels as medium to high-load tasks. In the experiment, participants were asked to watch a video, which primarily occupied their visual and auditory channels. During the execution of this NDRT (watching the video), participants were required to keep their gaze away from the road, and their right foot should be relaxed and off the brake pedal. Participants were unaware of the specific takeover events, when the system would issue a takeover prompt, and how it would do so before the takeover prompts occur.

The entire experimental route consisted of a bi-directional six-lane urban road with a speed limit of 60 km/h. The total length of the experimental road was 8.2 km, with sparse traffic flow and clear weather conditions. The vehicle used was an automatic transmission car, set to a speed of 50 km/h. The vehicle would only decelerate when the pedal change threshold reached 10%. As shown in *Figure 2*, the experimental route was divided into four segments, with each segment featuring one takeover request. The spacing between two adjacent takeover request locations is 2 km. The specifications of the four takeover scenarios were as follows:

- Scenario 1: As shown in *Figure 2(a)*, the vehicle was in driving automation mode when a pedestrian crossed the road from left to right at a speed of 1.4 m/s on a crossing. A takeover prompt was issued to the driver, who needed to timely take over the vehicle, and perform an emergency brake to stop before the pedestrian crossed the road.
- Scenario 2: As shown in *Figure 2(b)*, the vehicle was in driving automation mode when it approached a temporary construction site that required a lane change to the left. A takeover prompt was issued to the driver, who needed to timely take over the vehicle, and decelerate to a stop.

- Scenario 3: As shown in *Figure 2(c)*, the vehicle was in driving automation mode when a car on the right lane, without signalling, entered the lane of the automated vehicle at a speed of 40 m/s (slower than the automated vehicle). A takeover prompt was issued to the driver, who needed to timely take over the vehicle, and perform an emergency brake to avoid a collision.
- Scenario 4: As shown in *Figure 2(d)*, the vehicle was in driving automation mode when a traffic accident ahead blocked the lane. A takeover prompt was issued to the driver, who needed to timely take over the vehicle, and perform an emergency brake to stop.



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3 (d) Scenario 4

Figure 2 – Driving takeover scenarios

In the experiment, drivers were required to complete the four takeovers. The system was programmed to issue a takeover prompt when the time to collision (TTC) with a forward obstacle was set to 7 seconds. This study focused solely on the process of participants transitioning from performing a NDRT to taking over the vehicle. The actions taken by the participants after taking over were largely dependent on their personal driving experience and habits, there were no specific requirements set for these actions during the experiment.

3.4 Takeover prompts

Considering that single-level prompt methods do not achieve as high a takeover success rate as multi-level methods [40], the experiment did not further study single-level prompts. As shown in *Table 1*, the four takeover prompts are:
- Visual-auditory prompt
- Auditory-tactile prompt
- Visual-tactile prompt
- Visual-auditory-tactile prompt.

In the experiment, each takeover prompt appeared once. The order of the takeover scenarios remained unchanged, and a Latin square design was used to randomly arrange the order of appearance of the takeover prompts to reduce sequence errors in the experiment.

Table 1 – User interfaces for takeover

No.	Takeover prompt protocol	Specification
1	Visual-auditory(V-A)	The system displays a visual interface while simultaneously playing an auditory prompt.
2	Auditory-tactile(A-T)	The system plays an auditory prompt while the seat back vibrates.
3	Visual-tactile(V-T)	The system displays a visual interface while the seat back vibrates.
4	Visual-auditory-tactile(V-A-T)	The system displays a visual interface and plays an auditory prompt, while the seat back also vibrates.

The visual takeover prompt is shown in *Figure 3*, and it consists of two levels, i.e. a basic prompt and an urgent prompt. As it is shown in *Figure 3(a),* the basic prompt appears in the form of a pop-up window in which are the red text "Please take over the vehicle!" and an icon illustrating a steering wheel with red hands on it. Meanwhile, the screen was covered with a red floating layer with transparency of 70%. If the system does not detect a takeover action (such as pressing the brake pedal or a significant change in speed) within 2 seconds after the appearance of the basic prompt, an urgent prompt will pop up. The urgent prompt also appears in the form of a pop-up window, but the size of the window and the icon are both larger than that of the basic prompt. Besides, the transparency of the red floating layer is 50%, see *Figure 3(b)*. The design rationale is that using a hierarchical takeover prompt method can help drivers identify sources of risk and effectively enhance their motivation to take over [32].

(a) Basic Prompt

(b) Urgent Prompt

Figure 3 – Graphic user interface of visual takeover prompt

A voice generator (www.xunjie.com) was used to produce the audio prompt, with the takeover voice prompt text being "Please take over the vehicle immediately". The voice source was set to a standard Mandarin female voice with a speech rate of 3 characters per second. The prompt volume was measured with a decibel meter, averaging 72.2 dB. The output format was WAV, which was imported into the driving scenario design software and played through a speaker during the experiment. The tactile prompt used a vibrating seat back as the carrier, with the vibration mode set to a continuous vibration at level 1. The vibration parameters were 2.2 m/s^2 and 200 Hz, with a duration of 3 seconds.

3.5 Experimental procedure

Initially, participants are invited to sit in the driver's seat, sign a consent form and fill in some personal information, and then experience a driving automation takeover scenario (different from the experimental scenario) to familiarise themselves with the driving simulator and data collecting equipment. During this time, the experimenter explains the experimental procedures and objectives to the participants, informs them of, and demonstrates the takeover steps. Participants are asked to read the experimental instructions, and once they are ready, the experiment begins.

As shown in *Figure 4*, once the experiment starts, the vehicle operates in automated mode in the middle lane. Participants perform a NDRT which involves watching a video prepared in advance. The content of the video was a popular TV series at that time. The engaging clips are played to attract the participants' attention. Whenever the vehicle reaches a designated takeover point, the system randomly offers one of the four takeover prompts. Ten seconds later, regardless of whether the takeover is successful, the experiment pauses. The vehicle then returns to driving automation mode within 5 seconds and continues to the next scenario.

Upon receiving a takeover prompt, participants must grasp the steering wheel with both hands and press the brake pedal to decelerate the vehicle based on the traffic conditions on the road. If the participant performs these actions and prevents the vehicle from colliding with any obstacles ahead, the takeover is considered successful. The vehicle switches to manual driving mode, and thereafter, the participant may operate the vehicle as per the road conditions (e.g. steering). If the participant fails to complete the takeover actions within the set time or collides with an obstacle ahead, the vehicle will stop, and the takeover is deemed failure. After passing through four takeover points, the vehicle drives to the terminus, and the experiment concludes.

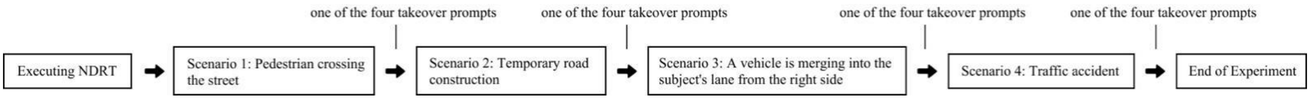


Figure 4 – Experiment procedure

3.6 Data collection

Since drivers require time to process displayed information and regain awareness, takeover reaction time should not be the only index for evaluating the effectiveness of in-vehicle HMI. However, improved prompting methods and situation awareness can mitigate the negative impact of extended takeover reaction times due to additional semantic information processing [41–43]. This study primarily collects data on takeover success rate, takeover time and takeover quality for analysis. The duration of the experiment was approximately 30 minutes for each participant.

Takeover time can be divided into takeover reaction time and takeover execution time. Takeover reaction time is defined as the time it takes for the participant's gaze to shift from a NDRT to the driving screen and initiate a takeover action after the system issues a takeover prompt. Takeover execution time is defined as the duration from when the participant begins physical movements to when the takeover action is completed, including the time taken to grasp the steering wheel and press the brake pedal to decelerate the vehicle. Total takeover time is the sum of these two, and it is generally believed that the smaller the takeover time, the better the takeover performance.

The mean longitudinal deceleration, lateral acceleration and minimum TTC after vehicle takeover are chosen as indicators of takeover quality. Longitudinal deceleration refers to the magnitude of braking deceleration produced by the vehicle along the direction of travel; lateral acceleration refers to the magnitude of braking acceleration produced by the vehicle moving sideways. Both metrics are commonly used to assess the stability of vehicle driving, and under the assumption that driving habits are not considered, it is generally believed that higher values indicate a more urgent braking process [44]. The minimum TTC, the shortest time until collision with an obstacle ahead when the takeover is successful, is often used in driving experiments to judge the urgency of the takeover process and assess the probability of traffic collisions [45]; the smaller the value, the higher the probability of collision and the more dangerous the situation.

4. RESULTS

4.1 Takeover success rate

During the experimental process, 6 instances of errors occurred involving 6 participants who were unfamiliar with the experimental requirements. These errors included premature takeovers, prolonged observation of the road, and failure to take over the vehicle, leading to abnormal data records. Therefore, these anomalous data needed to be excluded.

In the experiment, 30 participants completed a total of 120 takeovers. After excluding 6 anomalous instances, a total of 114 takeovers were completed, with 101 being successful. This results in an overall success rate of 88.60%. There were 13 failures, with 8 occurring after V-T prompts, 2 occurring after V-A prompts, 2 occurring after A-T prompts, and 1 occurring after V-A-T prompts, as shown in *Figure 5*. The collected data were processed and analysed by IBM SPSS Statistics 26.

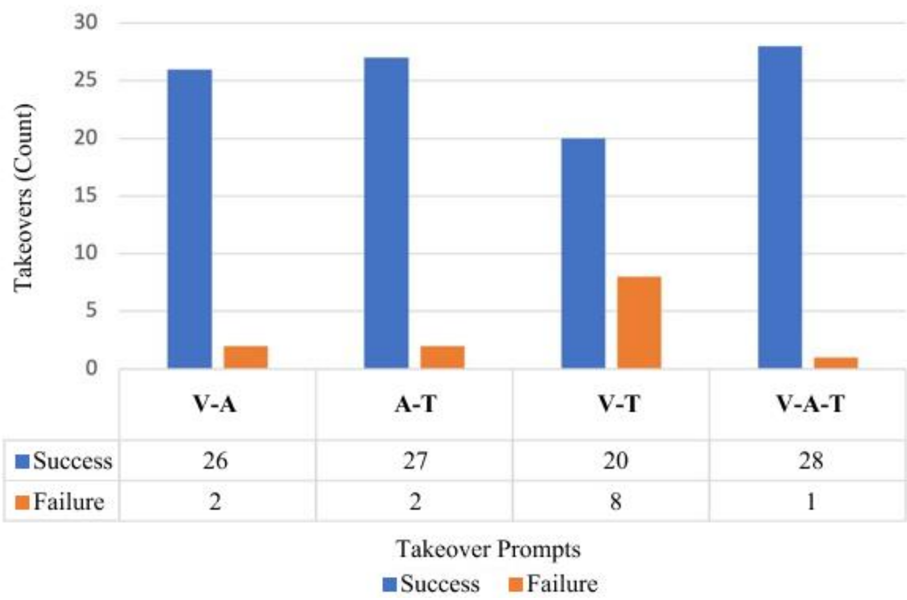


Figure 5 – Takeover success rate

4.2 Takeover time

The 114 takeover data were used as the total sample size, with the takeover reaction times under all four takeover prompts showing a normal distribution, ranging from 0.76 to 4.03 seconds. Samples of takeover failures were concentrated in the interval where takeover reaction times exceeded 3.5 seconds, as shown in the histogram in *Figure 6*, which displayed an approximately normal distribution. All analysis results were given at a 95% confidence level.

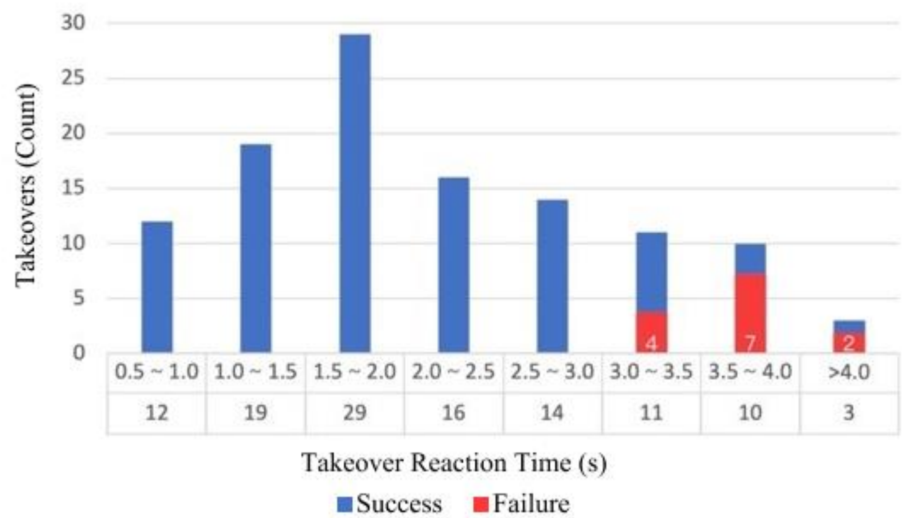


Figure 6 – Takeover reaction time

The distribution of takeover reaction times under different prompts is shown in *Figure 7*. A one-way ANOVA was used to test whether there were significant differences in takeover reaction times among the takeover prompts, where F is the test statistic and p represents significance. The results showed that takeover prompt significantly affects the takeover reaction time [$F(3,110) = 6.572$, $p < 0.001$], with V-A-T prompts having the shortest reaction time (0.99 ± 0.23 s) and V-T prompts having the longest reaction time (2.82 ± 0.63 s). Compared to V-A-T prompts, V-A prompts had a slightly increased reaction time (1.43 ± 0.51 s), but the difference was not significant ($p = 0.076 > 0.05$). A-T prompts (1.54 ± 0.50 s) showed a significant difference in reaction time compared to V-A-T prompts ($p = 0.042 < 0.05$). The reaction time of A-T prompts was slightly longer than that of V-A prompts, but there was no significant difference in reaction times between them ($p= 0.604 > 0.05$).

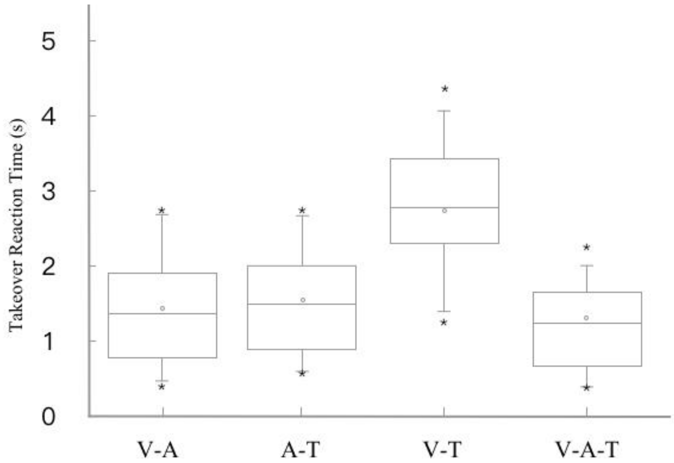


Figure 7 – Reaction time of each takeover prompt

The comparison of takeover execution time under different prompts is shown in *Figure 8*. Results indicate that takeover prompt significantly impacts takeover execution time [F (3,110) = 10.789, p< 0.001]. V-T prompts result in the longest execution time (3.51 ± 0.58 s), which was significantly different from V-A-T prompts (2.07 ± 0.43 s) (p < 0.001). The total takeover execution time under V-A prompts (2.12 ± 0.57 s), A-T prompts (2.01 ± 0.52 s) and V-A-T prompts were similar, with no significant differences between any two prompts of them (p > 0.05). According to the recorded videos of the experiment, some participants take over the steering wheel and brake pedal with a wide range of body movements, which shortened the emergency handling time and resulted in similar takeover execution time despite minor differences in reaction time.

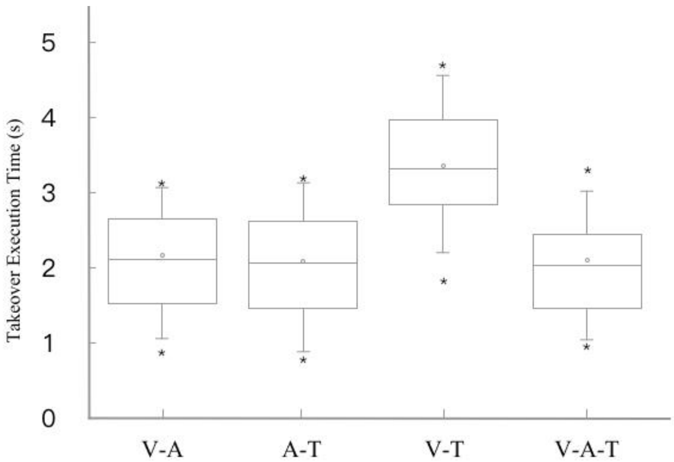


Figure 8 – Takeover execution time of each takeover interface

4.3 Takeover quality

Longitudinal deceleration

The comparison of mean longitudinal deceleration under different takeover prompts is shown in *Figure 9*. The analysis indicates that the type of takeover prompts has a significant impact on mean longitudinal deceleration [F (3,110) = 0.661, p = 0.011 < 0.05]. V-T prompts exhibited the highest longitudinal deceleration. Evidence from the video shows that this was due to participants needing to apply emergency braking to compensate for the longer takeover reaction times, thereby increasing longitudinal deceleration.

V-A-T prompts had the lowest longitudinal deceleration, and the deceleration after V-A prompts was slightly higher than after V-A-T prompts, but the difference was not statistically significant (p= 0.758). When there was sufficient takeover time, participants had enough time to control vehicle braking smoothly rather than having to emergency brake. The longitudinal deceleration in A-T prompts was significantly increased compared to V-A prompts (p= 0.043 < 0.05). Combined with the results of V-A-T prompts, it suggests that adding tactile cues in the takeover prompts increases the longitudinal deceleration. This implies that tactile vibrations may induce a sense of urgency in participants during takeover. Despite having sufficient takeover time, participants reflexively adopted a more urgent braking method due to the significant mental resources occupied by NDRTs during the experiment.

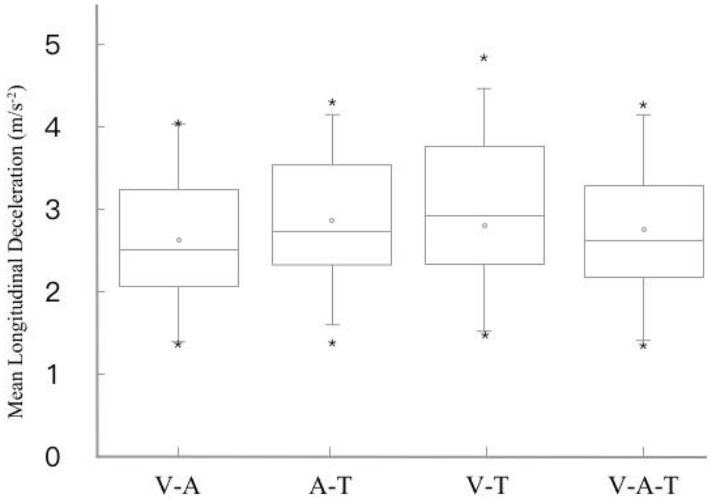


Figure 9 – Longitudinal deceleration of each takeover interface

Lateral acceleration

The comparison of mean lateral acceleration under different takeover prompts is illustrated in *Figure 10*. The results did not show a significant impact of the type of takeover prompts on lateral acceleration [F (3,110) = 0.049, p = 0.066 > 0.05]. In the experiment, most participants did not resort to emergency steering to avoid accidents, resulting in lower lateral accelerations. This also demonstrates the viability of the four types of prompts in providing takeover prompts, as they are likely to ensure the lateral stability of the vehicle during takeovers.

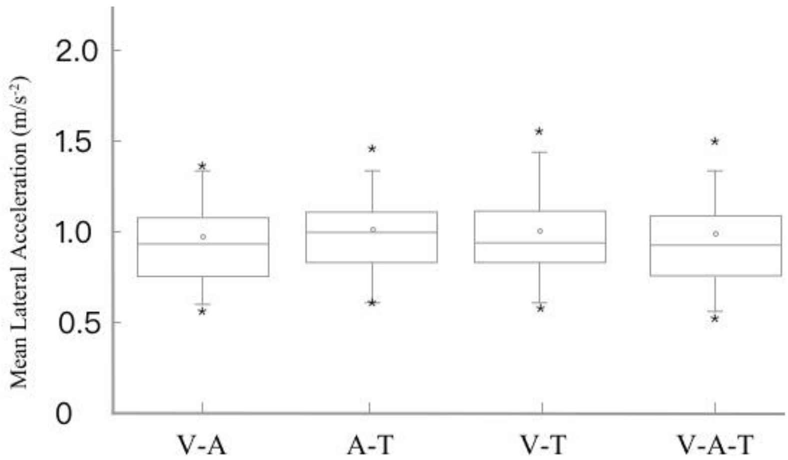


Figure 10 – Lateral acceleration under each takeover interface

Minimum TTC

The minimum time-to-collision (TTC) of all takeover prompts is illustrated in *Figure 11*. The collected data did not distribute normally, then Kruskal-Wallis test was employed to determine if there were significant differences in minimum TTC under different takeover prompts, where H is the test statistic and p represents significance.

The results showed that the takeover prompt had a significant effect on the minimum TTC (H = 17.601, p= 0.026 < 0.05). The mean ranks for each prompt were as follows: V-A prompts had a mean rank of 152.26 (n=28); A-T prompts had 140.77 (n=29); V-T prompts had 97.39 (n=28); and V-A-T prompts had 163.17 (n=29). V-T prompts exhibited the smallest minimum TTC, and there were significant differences between V-T prompts and V-A prompts (p = 0.023 < 0.05), V-T prompts and V-A prompts (p = 0.013 < 0.05), and V-T prompts and V-A-T prompts (p = 0.009 < 0.05). No significant differences were found in the other pair analysis.

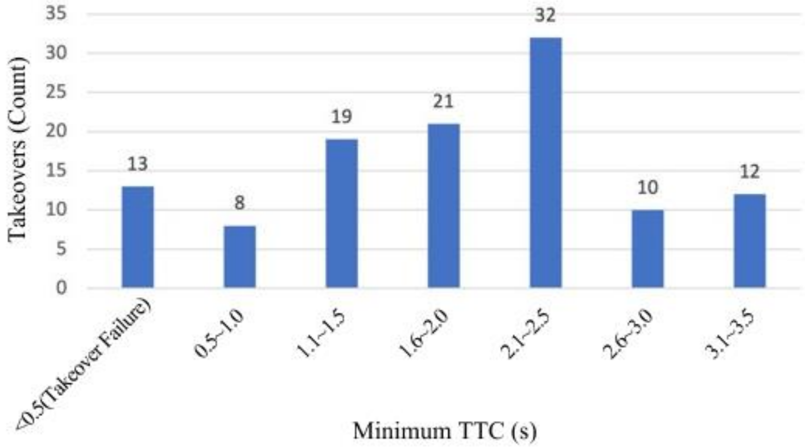


Figure 11 – Minimum TTC

Combined with previous analysis of takeover execution time, it appears that under the premise of successful takeover, the duration of the takeover significantly influences the minimum TTC; longer takeover execution times result in shorter minimum TTCs. Driving scenarios with a minimum TTC of less than 1 second are typically considered as near collisions [46]. In the experiment, there were 21 samples (18.42%) that met the criteria for near-collision (see *Figure 12*). V-T prompts had the highest probability of near-collision at 35.71%.

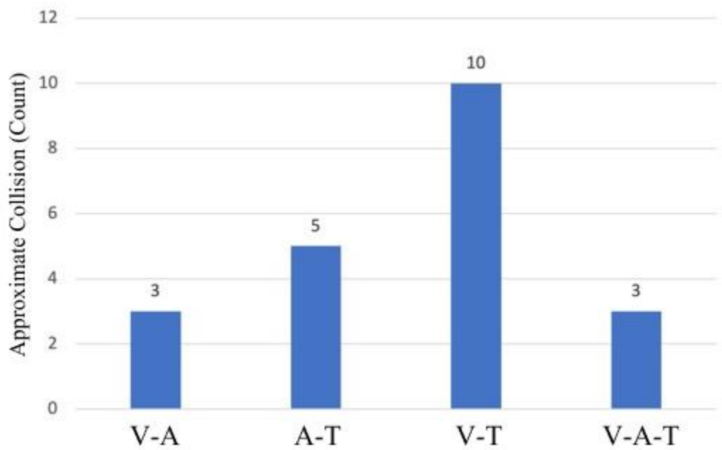


Figure 12 – Approximate collision samples

From the analysis of the three indicators of takeover quality, it can be seen that the longitudinal quality of vehicle takeover improves with increased time allotted for takeover. More urgent takeovers lead to greater longitudinal acceleration and shorter minimum TTC. Moreover, excessively strong prompt methods may cause drivers to undertake emergency takeovers, allowing the vehicle to be quickly decreased to a safer speed, ensuring takeover time while increasing the combined acceleration during vehicle braking. The experiment did not reveal any significant changes in lateral acceleration after vehicle takeover under different prompts.

5. DISCUSSION

This study proposed four driving automation takeover prompts, namely visual-auditory prompts, auditory-tactile prompts, visual-tactile prompts and visual-auditory-tactile prompts. Utilising a driving simulator, takeover experiments were conducted to analyse the influence of these different prompts on takeover performance.

In terms of takeover time, V-T prompts had the longest reaction time, while V-A-T prompts had the shortest. This suggests that multimodal takeover prompts can reduce reaction times. Human observers can detect combinations of multisensory signals more rapidly than when each signal is presented individually [47]. When multiple senses simultaneously receive the same information, this can enhance perceived urgency and alerting effectiveness, thereby improving task processing efficiency and decreasing reaction times [48–50].

Multimodal prompts provide more sensory stimuli by incorporating visual, auditory and tactile stimuli. This makes it easier for drivers to notice the cues that signal takeover requests, thus enhancing their reaction. Moreover, when one sensory channel is occupied or disrupted, other sensory channels can provide information by sensing the corresponding stimuli of the prompts. This compensation mechanism could decrease the miss rate [51]. However, it is observed that the reaction time was the longest for the V-T prompts, which may be related to the absence of auditory cues. Current experiments have found that participants with auditory takeover requests (TORs) respond more quickly. Some studies discovered that takeover times are shorter for each TOR that includes language-based auditory cues [40, 49]. Nevertheless, whether the auditory channel is the primary factor in accelerating reaction times during NDRTs engagement requires further study.

Regarding the takeover quality, V-A-T prompts exhibited the least longitudinal deceleration, followed by V-A prompts. Furthermore, while V-A prompts and A-T prompts showed similar takeover times, A-T prompts resulted in increased longitudinal deceleration. Tactile prompts are often considered signals of urgency or importance [52], and the inclusion of tactile prompts can lead some drivers to subconsciously initiate emergency takeovers. This is particularly significant as tactile vibrations ranked first in takeover reactions, which may be attributed to conflicts between the driving task and NDRTs with visual and auditory resources, thereby shortening takeover times [53]. However, the addition of tactile prompts might prompt some drivers to take more urgent actions during takeover, thereby increasing the vehicle's longitudinal deceleration during braking. The results indicate that tactile prompts can serve as an effective method of takeover prompting, particularly when visual and auditory resources might be occupied by NDRTs. Even with that in mind, we still consider that tactile prompts could trigger emergency reactions from drivers and potentially affect the quality of the takeover.

V-T prompts showed significantly lower takeover success rates, takeover times and takeover quality compared to the other three prompts. Long time immersed in NDRTs can lead to a reduction in situation awareness below the level necessary for safely resuming manual control [54]. The absence of voice guidance requires drivers to immediately judge and acquire takeover information on their own upon being alerted, which increases the time needed to shift their gaze and the cognitive load on driving, thereby resulting in longer takeover times. This aligns with findings that explored the benefits of interacting with digital voice assistants during the driving automation process [55]. For some drivers, it requires more time and effort to recognise and understand tactile cues. This prolongs takeover time and decreases the success rates of takeovers, and potentially impacts the quality of the takeover. The experiment results indicated that auditory prompts are essential in designing takeover prompts.

V-A-T prompts effectively enhanced takeover motivation and reduced reaction time. However, there is no significant difference in total takeover time compared to V-A prompts and A-T prompts. The quality of takeover among these prompts also shows no significant difference. Although multimodal prompts can provide more kinds of stimuli to inform drivers of the takeover requests, it does not necessarily lead to better takeover quality. This redundant design may not always help drivers take over more quickly or control the vehicle more effectively. Previous research suggests two potential reasons for this. First, the presentation of information requires trade-offs, and an excess of information can lead to information overload, thereby requiring more time for drivers to process [56]. Second, if drivers are unfamiliar with one of the provided prompts, the information provided by prompts may be inconsistent with their cognition. This potentially confuses drivers and affects the effectiveness of the takeover [56]. In designing takeover prompts, we need to consider not only providing as much information as possible, but also how this information is presented to avoid information overload or inconsistency. Future research could explore how to effectively combine and deliver these prompts to improve takeover performance.

In the experiment, 21 near-collision samples were observed. According to interviews with the participants, most incidents were due to excessive immersion in watching videos, which led to reduced situation awareness and diminished preparedness for takeover. It is also reported that excessive immersion in watching videos would increase takeover time and reduce takeover efficiency [57]. Since the takeover process lasts only a few seconds, participants reported difficulty in fully regaining the driving context solely through takeover prompts, relying more on their own driving experience and judgement. The takeover involves three stages. Firstly, shift their attention from NDRTs to TOR stimuli. Secondly, establish patterns and situation awareness to make decisions and future predictions. Finally, execute manoeuvres to regain control [58]. Liu et al. [16] summarised the impact of additional semantic content in vehicle HMI on takeover, noting the importance of integrating urgency patterns and content, as well as the effectiveness and efficiency of transmitting additional semantic information in future designs of vehicle HMI.

6. CONCLUSION AND LIMITATIONS

In this research, we investigated the impact of the four prompts on takeover performance. The results indicated that prompts without auditory stimuli induce the longest reaction time, the lowest takeover success rate and the worst takeover quality. We highlighted the importance of auditory and tactile channels, which can more rapidly make drivers aware of TORs, enabling quicker reactions. The auditory prompts primarily rely on voice or nonverbal sound to convey the takeover requests to the driver. The sensitivity of the auditory perception makes prompts with auditory stimuli more effective than those without it. The tactile channel performs well in shifting the driver's attention but lacks clarity in its prompts, which could somewhat impact the vehicle's longitudinal deceleration during braking, thereby affecting takeover quality. As driving automation technology continues evolving, the findings of this study will help promote safer and more effective human-machine interaction designs. These findings are of significant guidance value for the design and usage of automated driving systems, especially in developing user interfaces and safety protocols.

Despite offering new insights, our study still has some limitations. Since the optimal presentation mode for each modality has not been explored or standardised, the choices of presentation modes and their combinations in this study may not necessarily be the most suitable. We explored multimodal interfaces combinations, which had different impacts on driving takeover performance, indicating that designing takeover prompts for automated vehicles requires careful consideration of how to combine multimodal stimuli while balancing various prompting methods to provide the most effective information without overloading the driver's perceptual and cognitive systems.

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REFERENCES

[1] SAE International. Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles - SAE international [Internet]. www.sae.org. 2021. Available from: https://www.sae.org/standards/content/j3016_202104/

[2] Melnicuk V, Thompson S, Jennings P, Birrell S. Effect of cognitive load on drivers' state and task performance during automated driving: Introducing a novel method for determining stabilisation time following take-over of control. *Accident Analysis & Prevention*. 2021;151:105967, DOI: 10.1016/j.aap.2020.105967.

[3] Li Q, et al. Drivers' visual-distracted take-over performance model and its application on adaptive adjustment of time budget. *Accident Analysis & Prevention*. 2021;154:106099–9, DOI: 10.1016/j.aap.2021.106099.

[4] Hadi AM, et al. Influence of passive fatigue and take-over request lead time on drivers' take-over performance. *Proceedings of the AHFE 2020 Virtual Conference on Human Aspects of Transportation*, 16-20 July 2020, USA, Springer, 2020, p. 253–259. DOI: 10.1007/978-3-030-50943-9_32.

[5] Pepin G, et al. Impact of mind-wandering on visual information processing while driving: An electrophysiological study. *Applied Cognitive Psychology*. 2020;35(2):508–516. DOI: 10.1002/acp.3773.

[6] Gold C, Körber M, Lechner D, Bengler K. Taking over control from highly automated vehicles in complex traffic situations. *Human Factors: The Journal of the Human Factors and Ergonomics Society*. 2016;58(4):642–652. DOI: 10.1177/0018720816634226.

[7] Körber M, Gold C, Lechner D, Bengler K. The influence of age on the take-over of vehicle control in highly automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2016;39:19–32. DOI: 10.1016/j.trf.2016.03.002.

[8] Du N, et al. Examining the effects of emotional valence and arousal on takeover performance in conditionally automated driving. *Transportation Research Part C: Emerging Technologies*. 2020;112:78–87. DOI: 10.1016/j.trc.2020.01.006.

[9] Wan J, Wu C. The effects of lead time of take-over request and nondriving tasks on taking-over control of automated vehicles. *IEEE Transactions on Human-Machine Systems*. 2018;48(6):582–591. DOI: 10.1109/THMS.2018.2844251.

[10] Eriksson A, Stanton NA. Takeover time in highly automated vehicles: noncritical transitions to and from manual control. *Human Factors: The Journal of the Human Factors and Ergonomics Society*. 2017;59(4):689–705. DOI:10.1177/0018720816685832.

[11] Gold C, Damböck D, Lorenz L, Bengler K.Take over!” How long does it take to get the driver back into the loop? *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 57*, p.1938 - 1942. DOI: 10.1177/1541931213571433.

[12] Wang HC, Guo Z, Rau PLP. The shorter takeover request time the better? Car-driver handover control in highly automated vehicles. Automation, *Collaboration, & E-Services*. 2022; pp.3–17. DOI: 10.1007/978-3-031-10784-9_1.

[13] Endsley MR. Toward a theory of situation awareness in dynamic systems. *Human Factors: the Journal of the Human Factors and Ergonomics Society* [Internet]. 1995;37(1):32–64. Available from: https://journals.sagepub.com/doi/10.1518/001872095779049543.

[14] Gilson RD, Human factors and ergonomics society. *Situation Awareness*. Santa Monica, Ca.: Human Factors And Ergonomics Society; 1995.

[15] Kim H, et al. A study on the effects of providing situation awareness information for the control authority transition of automated vehicle. In: *2019 International Conference on Information and Communication Technology Convergence (ICTC)*; 2019 Oct; Jeju Island, Korea. IEEE; 2019. p. 1394–1396. DOI: 10.1109/ICTC46691.2019.8939867.

[16] Liu W, et al. A literature review on additional semantic information conveyed from driving automation systems to drivers through advanced in-vehicle HMI just before, during, and right after takeover request. *International Journal of Human–Computer Interaction*. 2023;39(10):1995–2015. DOI: 10.1080/10447318.2022.2074669.

[17] Atakishiyev S, Salameh M, Goebel R. Incorporating explanations into human-machine interfaces for trust and situation awareness in autonomous vehicles. In: *2024 IEEE Intelligent Vehicles Symposium (IV)*; 2024 Jun; Jeju Island, Korea. IEEE; 2024. p. 2948–2955. DOI: 10.1109/IV55156.2024.10588812.

[18] De Winter JCF, Happee R, Martens MH, Stanton NA. Effects of adaptive cruise control and highly automated driving on workload and situation awareness: A review of the empirical evidence. *Transportation Research Part F Traffic Psychology and Behavior*. 2014;27:196–217. DOI: 10.1016/j.trf.2014.06.016.

[19] Weaver BW, DeLucia PR. A systematic review and meta-analysis of takeover performance during conditionally automated driving. *Human Factors: The Journal of the Human Factors and Ergonomics Society*. 2020;001872082097647. DOI: 10.1177/0018720820976476.

[20] Pfleging B, Rang M, Broy N. Investigating user needs for non-driving-related activities during automated driving. In: *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia*; 2016 Dec; Rovaniemi, Finland. ACM; 2016. pp. 91–99. DOI: 10.1145/3012709.3012735.

[21] Zhang N, et al. Influence of non-driving related tasks on driving performance after takeover transition in conditionally automated driving. *Transportation research Part F, Traffic psychology and behaviour*. 2023;96:248–264. DOI: 10.1016/j.trf.2023.05.009.

[22] Naujoks F, Purucker C, Neukum A. Secondary task engagement and vehicle automation – Comparing the effects of different automation levels in an on-road experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2016;38:67–82. DOI: 10.1016/j.trf.2016.01.011.

[23] Chen W, Sawaragi T, Hiraoka T. Adaptive multi-modal interface model concerning mental workload in take-over request during semi-autonomous driving. SICE *Journal of Control, Measurement, and System Integration*. 2021;1–12.DOI: 10.1080/18824889.2021.1894023.

[24] Zhang B, et al. Determinants of take-over time from automated driving: A meta-analysis of 129 studies. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2019:285–307. DOI: 10.1016/j.trf.2019.04.020.

[25] Petermeijer S, Doubek F, de Winter J. Driver response times to auditory, visual, and tactile take-over requests: a simulator study with 101 participants. In: *2017 IEEE International Conference on Systems, Man, and Cybernetics* (SMC); 2017 Oct; Banff, Canada. IEEE; 2017. pp. 1505–1510. DOI: 10.1109/SMC.2017.8122827.

[26] Houtenbos M, et al. Concurrent audio-visual feedback for supporting drivers at intersections: A study using two linked driving simulators. *Applied Ergonomics*. 2017 Apr. 60:30–42. DOI: 10.1016/j.apergo.2016.10.010.

[27] Talamonti W, et al. Mirage events & driver haptic steering alerts in a motion-base driving simulator: A method for selecting an optimal HMI. *Applied Ergonomics*. 2017;65:90–104. DOI: 10.1016/j.apergo.2017.05.009.

[28] Sanghavi H, Zhang Y, Jeon M. Effects of anger and display urgency on takeover performance in semi-automated vehicles. In: *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*; 2020 Sep; Virtual Event, DC, USA. ACM; 2020. pp. 48–56. DOI: 10.1145/3409120.3410664.

[29] Li S, et al. Evaluation of the effects of age-friendly human-machine interfaces on the driver's takeover performance in highly automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2019;67:78–100. DOI: 10.1016/j.trf.2019.10.009.

[30] Petermeijer SM, Cieler S, de Winter JCF. Comparing spatially static and dynamic vibrotactile take-over requests in the driver seat. *Accident Analysis & Prevention*. 2017;99:218–227. DOI: 10.1016/j.aap.2016.12.001.

[31] SELCON SJ, Taylor RM, Mckenna FP. Integrating multiple information sources: using redundancy in the design of warnings. *Ergonomics*. 1995;38(11):2362–2370. DOI: 10.1080/00140139508925273.

[32] Petermeijer S, Bazilinskyy P, Bengler K, de Winter J. Take-over again: Investigating multimodal and directional TORs to get the driver back into the loop. *Applied Ergonomics*. 2017;62:204–215. DOI: 10.1016/j.apergo.2017.02.023.

[33] Bazilinskyy P, et al. Take-over requests in highly automated driving: A crowdsourcing survey on auditory, vibrotactile, and visual displays. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2018;56:82–98. DOI: 10.1016/j.trf.2018.04.001.

[34] Diaconescu AO, Alain C, McIntosh AR. The co-occurrence of multisensory facilitation and cross-modal conflict in the human brain. *Journal of Neurophysiology*. 2011;106(6):2896–909. DOI: 10.1152/jn.00303.2011.

[35] Talsma D, Senkowski D, Soto-Faraco S, Woldorff MG. The multifaceted interplay between attention and multisensory integration. *Trends in Cognitive Sciences*. 2010;14(9):400–10. DOI: 10.1016/j.tics.2010.06.008.

[36] Tan X, Zhang Y. Analyzing driver strategy for scheduled takeovers under the effect of multi-stage takeover request design. *Proceedings of the Human Factors and Ergonomics Society*. 2023;67(1):1197-1203. DOI: 10.1177/21695067231192422. DOI: 10.1177/21695067231192422.

[37] Borowsky A, Zangi N, Oron-Gilad T. Interruption management in the context of take-over-requests in conditional driving automation. *IEEE Transactions on Human-Machine Systems*. 2022;52(5):1015–1024. DOI: 10.1109/THMS.2022.3194006.

[38] Jiang L, Wang X, Li Z, Zhang Y. Research on design model of human-machine interface of automatic driving takeover system based on user experience. *Lecture notes in computer science*. 2019;41–60. DOI: 10.1007/978-3-030-23538-3_4.

[39] Bazilinskyy P, de Winter JCF. Analyzing crowdsourced ratings of speech-based take-over requests for automated driving. *Applied Ergonomics*. 2017;64:56–64. DOI: 10.1016/j.apergo.2017.05.001.

[40] Forster Y, Naujoks F, Neukum A, Huestegge L. Driver compliance to take-over requests with different auditory outputs in conditional automation. *Accident Analysis & Prevention*. 2017;109:18–28. DOI: 10.1016/j.aap.2017.09.019.

[41] Kim S, van Egmond R, Happee R. Effects of user interfaces on take-over performance: A review of the empirical evidence. *Information*. 2021;12(4):162. DOI: 10.3390/info12040162.

[42] Schwarz F, Fastenmeier W. Augmented reality warnings in vehicles: Effects of modality and specificity on effectiveness. *Accident Analysis & Prevention*. 2017;101:55–66. DOI: 10.1016/j.aap.2017.01.019.

[43] Zhou H, Keita K, Itoh M, Satoshi K. Effects of explanation-based knowledge regarding system functions and driver's roles on driver takeover during conditionally automated driving: A test track study. *Transportation research Part F, Traffic psychology and behaviour*. 2021;77:1–9. DOI: 10.1016/j.trf.2020.11.015.

[44] Lu Z, et al. Human factors of transitions in automated driving: A general framework and literature survey. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2016;43:183–198. DOI: 10.1016/j.trf.2016.10.007.

[45] Happee R, et al. Take-over performance in evasive manoeuvres. *Accident Analysis & Prevention*. 2017;106:211–222.DOI: 10.1016/j.aap.2017.04.017.

[46] Young W, Sobhani A, Lenné MG, Sarvi M. Simulation of safety: A review of the state of the art in road safety simulation modelling. *Accident Analysis & Prevention*. 2014;66:89–103. DOI: 10.1016/j.aap.2014.01.008.

[47] Hecht D, Reiner M, Karni A. Multisensory enhancement: Gains in choice and in simple response times. *Experimental Brain Research*. 2008;189(2):133–143. DOI: 10.1007/s00221-008-1410-0.

[48] Politis I, Brewster S, Pollick F. Speech tactons improve speech warnings for drivers. In: *Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*; 2014 Sep; Seattle, WA, USA. ACM; 2014. pp. 1–8. DOI: 10.1145/2667317.2667318.

[49] Politis I, Brewster S, Pollick F. Language-based multimodal displays for the handover of control in autonomous cars. In: *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*; 2015 Sep; Nottingham, United Kingdom. ACM; 2015. pp. 3–10. DOI: 10.1145/2799250.2799262.

[50] Huang G, Steele C, Zhang X, Pitts BJ. Multimodal cue combinations: a possible approach to designing in-vehicle takeover requests for semi-autonomous driving. *Proc Hum Factors Ergon Soc Annu Meet*. 2019;63(1):1739–43. pp. 1739–1743. DOI: 10.1177/1071181319631053.

[51] Hancock PA, et al. Tactile cuing to augment multisensory human-machine interaction. *Ergonomics in Design The Quarterly of Human Factors Applications*. 2015;23(2):4–9. DOI: 10.1177/1064804615572623.

[52] Meng F, Spence C. Tactile warning signals for in-vehicle systems. *Accident Analysis & Prevention*. 2015 Feb 1;75:333–346. DOI: 10.1016/j.aap.2014.12.013.

[53] Faltaous S, Schönherr C, Detjen H, Schneegass S. Exploring proprioceptive take-over requests for highly automated vehicles. In: *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia*; 2019 Nov; Pisa, Italy. ACM; 2019. p. 1–6. DOI: 10.1145/3365610.3365644.

[54] Zeeb K, Buchner A, Schrauf M. What determines the take-over time? An integrated model approach of driver take-over after automated driving. *Accident Analysis & Prevention*. 2015;78:212–221. DOI: 10.1016/j.aap.2015.02.023.

[55] Mahajan K, Large DR, Burnett G, Velaga NR. Exploring the benefits of conversing with a digital voice assistant during automated driving: A parametric duration model of takeover time. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2021;80:104–126. DOI: 10.1016/j.trf.2021.03.012.

[56] Sarter NB. Multimodal information presentation: Design guidance and research challenges. *International Journal of Industrial Ergonomics*. 2006;36(5):439–445. DOI: 10.1016/j.ergon.2006.01.007.

[57] Zeeb K, Härtel M, Buchner A, Schrauf M. Why is steering not the same as braking? The impact of non-driving related tasks on lateral and longitudinal driver interventions during conditionally automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2017;50:65–79. DOI: 10.1016/j.trf.2017.07.008.

[58] Abbas-Zadeh M, Hossein-Zadeh GA, Vaziri-Pashkam M. Dual-task interference in a simulated driving environment: Serial or parallel processing? *Frontiers in Psychology*. 2021;11. DOI: 10.3389/fpsyg.2020.579876.