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# Constructing the behavioral sequence of the takeover process—TOR, behavior characteristics and phases division: A real vehicle experiment

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ABSTRACT

Autonomous driving will still use human–machine co-driving to handle complex situations for a long term, which requires the driver to control the vehicle and avoid hazards by executing appropriate behavioral sequences after takeover prompts. Previous studies focused on the division of static behavioral indicators and major phases in the initial phase of takeover, while lacking the construction of behavioral sequences based on the dynamic changes of behavioral characteristics during the takeover process. This study divides the takeover process in a detailed manner and investigates the impact of audio types on the behavioral sequence at each phase. 20 professional drivers performed the NDRT in autonomous driving mode on real roads, and after receiving audio prompts, they took over the vehicle and performed hazard avoidance maneuvers. The results show that the behavioral characteristics could construct the behavioral sequence of different phases, with the dynamic characteristics of the takeover operation change. In addition, different types of audio prompts will affect the timing of the takeover operation and its driving performance. Choosing different audio prompts or combinations can help improve the effect of taking over the vehicle. This study helps to provide guidance on the design of human–machine interaction for behavior optimization at different phases, so that guiding the driver to take over the vehicle safely and effectively.

## 1. Introduction

Human-machine co-driving is one of the great challenges of autonomous driving. NHTSA provisions historically allowed fully autonomous driving without the aid of a steering wheel and other manual controls (NHTSA, 2022). However, it is undeniable that, as long as fully autonomous driving technology (L5) has not been realized, road regulations and supporting infrastructure have not been improved (SAE, 2021), for a long time in the future, we will still need humans to take over vehicles to deal with automation technology problems brought by complex environments (Damböck et al., 2012b; Dokic et al., 2015; Schwarting et al., 2019). Conditional autonomous driving as well as highly autonomous driving (L3&L4) allows drivers to engage in non-driving-related tasks (Merat et al., 2012), but after a takeover request (TOR) occurs, the driver needs to regain control of the vehicle (Petermeijer et al., 2017a).

The takeover process in autonomous driving involves complex human factors (such as attention, psychology), and failure to effectively take over the vehicle and effectively control the driving behavior during the takeover process may lead to serious traffic safety hazards (Desmond et al., 1998; Naujoks et al., 2018; Schömig et al., 2015). In particular, existing research has shown that driving performance decreases with increasing level of automation (Dogan et al., 2019; Roche et al., 2020), requiring the driver to cope with the task transition from autonomous driving to human driving after a takeover request has occurred, and to successfully control the vehicle and avoid dangers by executing an appropriate sequence of actions (Casner & Hutchins, 2019; Damböck et al., 2012a). As in the aviation industry today, pilot interaction with automation has become a standardized practice: from takeover/handover, to early warning, to avoidance of aviation hazards, and other behaviors that adhere to strict operational procedures. As a result, we are enjoying historically low airline crash rates (Casner & Hutchins, 2019). Therefore, it is crucial to understand how TOR affects the behavioral sequence of the takeover process, and how the behavioral sequence is constructed.

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### 1.1. The influence of TOR methods on the takeover process

#### 1.1.1. Three modalities of TOR

Currently, there are three modalities of TOR: Visual, Tactile, and Auditory. From the visual perspective, research focuses on the HMI design of the vehicle's central control screen to improve the effect of taking over the vehicle (Naujoks et al., 2018; Wandtner et al., 2018; Zeeb et al., 2016), in which the time it takes for the driver to react to an alert may depend on the amount and type of information displayed on the interface (Gold et al., 2013), and increasing the forecast information of the surrounding environment can significantly improve the takeover efficiency (Ou et al., 2021). However, visual cues, while conveying warnings, can themselves create a certain degree of risk of distraction (Hajiseyedjavadi et al., 2018). In addition, more than 50% of visual warning signals are virtually ineffective depending on the user's reaction time (van der Heiden et al., 2019).

From the tactile perspective, the tactile sense is considered as an effective aid for the other modalities (Erp, 2002; Wan & Wu, 2018), and compared with static tactile signals, those including direction information have significant advantages in terms of the effect of taking over (Meng et al., 2015; Schieben et al., 2014). Although tactile signals can effectively facilitate takeover, their fatal flaw is the limited amount of information that can be conveyed and the difficulty in identifying such information, which leads to higher levels of annoyance and poorer user experience (Politis et al., 2015), thus requiring other modalities to achieve the best warning effect (Hong & Yang, 2022; Petermeijer et al., 2017a).

Therefore, auditory modality is being widely used in the design of human–computer interaction in autonomous vehicles because of such advantages as detailed information transfer, spatial independence, and lack of intrusive problems (Naujoks et al., 2016; Petermeijer et al., 2017b; Sabic et al., 2021), especially in the design of takeover for current L3 vehicles (Huang & Pitts, 2022a). Compared with visual prompts, auditory ones can effectively and quickly wake up distracted drivers (Bazilinskyy & de Winter, 2015). In addition, audio and multi-modal alerts containing audio can effectively shorten the driver's reaction time (Geitner et al., 2019) and improve the experience of autonomous driving (Kuiper et al., 2020); studies have shown that compared to tactile prompts, auditory ones can better support the driver's speed perception of the vehicle in a comparison of multiple modalities of prompts (Yang & Ferris, 2020).

#### 1.1.2. Correlation between audio and takeover behavior

The driver's reception of audio information is a process of external stimulus-behavioral response, and the audio prompt of the takeover can effectively influence the driver's behavioral process of taking over the vehicle.

First, audio prompts have varying degrees of influence on takeover response in terms of timing. For example, drivers' cautionary responses were more pronounced when the underlying frequency of the prompt was higher compared to lower frequency sounds (Lewis et al., 2017). From previous simulator studies comparing abstract warning tones and voice warnings, it was shown that in non-emergency driving situations, abstract warning tones had shorter acknowledgement times; in critical situations, voice warnings had shorter response times (Forster et al., 2017). A comparison between siren sounds and voice requests for takeover showed that siren sounds had shorter response times than voice alerts when taking over complex driving tasks, because drivers would mostly choose to listen to the full voice message and then perform the operation (Naujoks et al., 2014).

Second, audio prompts correlate with the effect on vehicle handling. For example, compared with standard voice prompts, electronic voice can help drivers take over the vehicle faster and successfully complete behavioral operations such as lane changing and obstacle avoidance (Naujoks et al., 2016). And with a 5 s takeover lead time, although there was no difference in the takeover time, takeover with a male voice cues had greater lateral control behavior compared to that with a female voice, while a female voice produced greater vertical control behavior (Wang et al., 2022). In addition, when comparing the abstract warning tone with the electronic voice takeover cue, the former resulted in a greater angle of steering wheel turning (Hong & Yang, 2022).

Finally, there are potential effects of audio prompts on physiological and psychological behavior. For example, when additional audio prompts are added after the warning tone, drivers tend to pay less attention to the visual HMI as well as the vehicle surroundings during independently executed maneuvers (Naujoks et al., 2017). Additional research has shown that audio prompts that inform the reason for the takeover (e.g., description of the loop takeover scenario, road conditions) (Li et al., 2018; Li et al., 2019), as well as the use of polite cues can enhance the drivers' social presence and restore their trust in autonomous driving (Lee & Lee, 2022), resulting in a better interaction experience.

In summary, this paper investigates the behavioral characteristics of the audio-influenced takeover process with the audio-prompted TOR as the dominant feature.

### 1.2. Behavioral characteristics of the takeover process

The behavioral characteristics of the takeover process are externally manifested in physiological, psychological and operational behavior. Survey research shows that 97% of people cannot focus on multiple things at the same time (Watson & Strayer, 2010), and multi-threaded operations will consume a lot of mental workload compared to operations performed in a certain sequence (Rubinstein et al., 2001); From the perspective of behavior theory, drivers' operation sequence is the habit of operating the vehicle formed by the accumulated driving training (Yin & Knowlton, 2006), and such habitual behavior is shaped by the experience dependence of the ganglion circuit (Da Cunha et al., 2012), suggesting that the driver's driving behavioral manipulation can be triggered by external or internal stimuli, which can be done without constant conscious supervision.

#### 1.2.1. Research on physiological and psychological behavior

The physiological and psychological characteristics of the driver's behavior determines that the level of an individual's operational response during the takeover process is lower than during manual driving. For example, the driver's heart rate and pupil diameter amplitudes remain at their peaks for several seconds after a TOR is issued, and the driver's psychological and physiological changes prolong the reaction time (Alrefaie et al., 2019). At the same time, studies have shown that there is a strong relationship between self-reported trust, visual gaze behavior, and electrodermal activity: the higher the level of self-reported trust, the less attention the driver paid to the road; the more attention he paid to secondary tasks unrelated to driving, the lower the driver's electrodermal activity (Walker et al., 2019). Additionally, new research shows that when NASA-TLX is used as an indicator of mental workload, changes in pupil diameter, number of saccades, duration of saccades, and number of fixations are efficient indicators of mental workload (Chen et al., 2022).

At the same time, research on the psychological characteristics of drivers during takeover is transitioning from earlier forms of subjective questionnaire assessment to accurate characterization by objective quantitative means, such as electrocardiography (ECG), electroencephalography (EEG), electrodermal (EDR), functional near-infrared spectroscopy (fNIRS) (Balters et al., 2021; King et al., 2020; Lin et al., 2013; Melnicuk et al., 2021; Radhakrishnan et al., 2022; Ruscio et al., 2017) etc. In terms of ECG, studies have reflected cognitive state changes and risk perception during autonomous driving by ECG signals (heart rate, ERP) (Melnicuk et al., 2021; Ruscio et al., 2017). In addition, the combination of blink duration, eye-fixation-related potentials (EFRPs) and auditory-evoked potentials (AEPs) can be used to assess the amount of individual attention allocated to visual and operational resources depending on the driving situation (Kimura et al., 2022). In the case of EEG signals, for example, a comparison of EEG spectral features on autopilot drowsiness arousal revealed that audio cues reduced drowsiness but did not immediately lead to alertness (Lin et al., 2013); later, it was found that the delta-band power peak of the frontal component of the brain increased significantly when the driver was in a time-stressed situation, suggesting that under stressful conditions, drivers would subconsciously prepare for unexpected situations (King et al., 2020). However, the above are contact detections, which will interfere with the normal operation of the driver and have great limitations because of the high requirements of the experimental environment.

The eye movement characteristics in the driver's visual behavior make it clear that the individual's visual shift during the takeover process can easily lead to distraction, which leads to the potential risk of takeover driving. For example, it has been found that the percentage of average driver gazes on the central instrument panel (autonomous driving system) has a significant trend of increasing within 6 s after a TOR is issued (Dogan et al., 2017). It has been found through driving simulators that the driver's horizontal line of sight is generally more dispersed when driving autonomously than when driving manually (Louw & Merat, 2017). Moreover, during the takeover process, the driver's visual fixation area is mainly the road environment area (R. Clark et al., 2019). In addition to this, many studies measure the visual characteristics and driving performance of the driver after taking over the vehicle with such indicators as blink frequency (Du et al., 2020), pupil diameter (Li et al., 2020b), and time when eyes are off the road (Clark & Feng, 2017). In summary, the crucial reason for choosing to use eye tracker in this paper is to mitigate the effects of contact devices on driving operations in order to obtain realistic behavioral data.

#### 1.2.2. Research on operational behavior

The driver's operating behavior specifies the initial operating actions for a driver takeover for a specific takeover scenario. Studies typically use a combination of operational behavior and takeover performance to measure takeover effectiveness.

Takeover performance measures the quality of the takeover maneuver, and measures and metrics used in different studies include longitudinal/lateral acceleration, Time to collision (TTC), driving speed, the maximum steering wheel turning angle, percentage of brake/throttle pedal position, Standard deviation of lateral position (SDLP) (Agrawal & Peeta, 2021; Dogan et al., 2017; Saito et al., 2022; Wu et al., 2022; Zeeb et al., 2016) etc.

Operational behavior tends to correlate with the timing of behavior occurrence. For example, in the collision avoidance scenario, drivers prefer to steer the vehicle via the steering wheel rather than brake after receiving a takeover request (Blommer et al., 2017; Wang & Soeffker, 2019), and there is a temporal correlation between turning the steering wheel first and then braking for a lane changing operation (Wang & Soeffker, 2019). In the rear-end scenario, the time to place the hand on the steering wheel (0.7 s) is longer than the time to place the foot on the brake pedal (0.6 s), and although the driver has the choice to change the lane or stop, the former is chosen in 90% of cases (Morando et al., 2020). In contrast, in the system failure scenario, subjects whose drivers received a takeover request and used their hands and feet simultaneously to operate the vehicle had shorter reaction times (4.3 s vs. 5.54 s) than those whose hands and feet were not used simultaneously (Payre et al., 2017), and it was additionally found that drivers who frequently engaged in secondary tasks would unconsciously make braking maneuvers as a way to buy time (Zeeb et al., 2017). Longer automation durations appear to lead to lower performance (e.g., longer response times, more uncontrolled maneuvers, greater acceleration) than shorter automation durations (Samani et al., 2022). Further studies have shown that takeover performance decreases with age when drivers are relatively fatigued and drowsy, but increases with experience resulting in better takeover quality in unexpected situations (Agrawal & Peeta, 2021), a side note to the importance of regulating takeover operations. Also, providing a more adequate takeover lead time (9 s vs. 18 s) helps drivers to detect hazards earlier and avoid them in advance (Pipkorn et al., 2022). Even though drivers were required to continuously monitor the road, the requirement to keep their hands on the wheel and stay ready to take over did not result in earlier steering behavior than in the case where their hands were taken off the wheel (Pipkorn et al., 2021b). Furthermore, most of the previous studies have been dominated by studies using driving simulators, and these data have not been validated in the real world.

To achieve effective takeover of autonomous vehicles by human drivers, we need to consider not only the static behavioral indicators mentioned above. More importantly, we need to study the sequence of dynamic features during the takeover process (i.e., the sequence of operational behaviors associated with time and performance), and finally find a universal law that can reflect the behavioral characteristics of the autonomous vehicle's takeover process, that is, the behavioral sequence.

### 1.3. Behavioral phase design during the takeover process

#### 1.3.1. Problems and exploration

To date, the consensus reached by existing research is that the takeover process consists of a series of consecutive phases. The takeover process involves at least two major phases, namely the takeover preparation phase and the post-takeover phase. 1) The takeover preparation phase means that after the TOR signal is issued, the driver needs to make preparations for taking over, during which the vehicle is still in the state of autonomous driving. During this phase, the driver needs to shift his/her visual attention to the road, perceive TOR information, and evaluate the conditions of the driving environment, put his/her hands on the steering wheel, or his/her feet on the pedals, preparing to take over the vehicle (Banks & Stanton, 2019; Petermeijer et al., 2016; Zeeb et al., 2015). 2) The post-takeover phase refers to the period during which the driver performs vehicle operations. The driver needs to think and decide his/her course of action, and then gain control of the vehicle (from autonomous to manual) by turning the steering wheel or pressing the brake pedal. After the driver is in control of the vehicle, effective driving maneuvers are required to avoid risks (Huang & Pitts, 2022a; Mcdonald et al., 2019). However, the problem with the two phases is that they are too broadly defined and do not have clear start and end points, and they lack the depth of behavioral characteristics that would support the construction of a behavioral sequence. This is demonstrated by the fact that in the case of obstacle avoidance, the task of taking over is completed by avoiding the obstacle, while in the case of lane changing, the task is completed by changing to another lane, and in addition, stopping for unavoidable hazards is also an option. This leads to inconsistency in the definition of the end time of the behavior due to the inconsistent goal of the takeover task in different cases, so we believe that all of the above actions can be classified as "avoidance behavior" in response to hazards.

In recent years, an increasing number of studies have attempted to extend and segment the takeover phases. Many studies have focused on HMI design for the takeover preparation phase, from the selection of multiple modalities (Yang & Ferris, 2020) to the quantification of TORlts (Wu et al., 2022), and the research is gradually extended to letting the autonomous driving describe the environmental information 30 s before the TOR is issued (Saito et al., 2022). In addition, some studies have focused on the effect of takeover signal direction (ipsilateral versus contralateral) and lead time (4 versus 7 s) on the takeover performance during the takeover preparation phase and the post-takeover phase (Huang & Pitts, 2022b).

For the post-takeover phase, studies have not only focused on the avoidance of the first hazard (Cao et al., 2021; Eriksson et al., 2019) but also advance to more subsequent explorations of operational behavior and state recovery. From the perspective of handling performance, a considerable number of results reflect more instability in the first avoidance after the driver takes over the vehicle compared to the return to the original lane (Huang & Pitts, 2022b; Li et al., 2018; Ou et al., 2021; Pipkorn et al., 2022). And, from the perspective of situation awareness (SA), these studies further divided the post-takeover phase into the phase of SA acquisition and the phase of SA ending, believing that the vehicle could run stably and safely only when the driver had enough SA to operate the vehicle (Chen et al., 2021). More importantly, it would take longer time (more than 40 s) for the driver's physiology and psychology to return to the state of natural driving after he/she started to control the vehicle (Kim et al., 2021; Melnicuk et al., 2021). This means that even if the driver has avoided the first hazard, his or her handling ability and psychological state are still not sufficient to deal with subsequent potential hazards, and secondary accidents are still possible.

Based on existing research results, it can be observed that the existing research focuses on the occurrence of the initial behavior of the takeover process after the TOR is issued and the instantaneous index evaluation of the takeover process. However, research on dynamic driving behavior during takeover requires further and in-depth research. In addition, there is a lack of research that comprehensively considers the relationship between drivers' visual behavior, cognitive changes in situational awareness, and operational characteristics. We believe that the takeover process should be divided more finely according to the dynamic changes in the behavioral characteristics of the takeover process.

#### *1.3.2. Four-phase division of behavioral characteristics*

To approach this dearth of the dynamic evolution law of the driver's takeover behavior in the comprehensive process of takeover, we divide the takeover process into four phases according to the time series according to the behavior characteristics (shows in Fig. 1):

1) Preparing for takeover phase: This phase refers to the phase between the time when the vehicle issues TOR (time point zero) and the time when the driver makes an action to prepare to take over the vehicle. The preparatory action is defined as the first behavioral input after the driver receives TOR, including placing hands on the steering wheel, placing feet on the brake pedal (Huang & Pitts, 2022b; Petermeijer et al., 2016), and obvious preparations for postural adjustment (Zeeb et al., 2015).

2) Decision-making reaction phase: This phase refers to the phase between the end of the preparing for takeover phase and the completion of the first decision-making act. The driver needs to think and decide his/her course of action (Chen et al., 2021), then gain control of the vehicle (from automatic to manual), and complete the first decision-making behavior to avoid dangers. Based on the previous inductive definition, we can now define the end time of "completion of the first circumvention", i.e., the point in time when the first circumvention is completed. This phase is characterized by the first control of the vehicle and the occurrence of the avoidance behavior, which ends at the "point of completion of the first avoidance behavior".

3) Stabilization control phase: This phase refers to the phase from the point at which the decision-making reaction phase ends to the point at which the throttle pedal is finally stabilized to achieve a return to driving status. After completing hazard avoidance, the driver needs to disengage from the risk site (make his/her own decision whether he/she needs to return to the original lane) and finally stabilize the vehicle speed in order to return to a normal state of driving. Considerable research has emerged on the changes in handling performance after the takeover and the longer time required for the return of psychological and physiological behaviors to the natural driving state (Huang & Pitts, 2022b; Li et al., 2019; Melnicuk et al., 2021), and agrees that there is a process known as the need to "stabilize" post-takeover operating behavior (Kim et al., 2021; Marberger et al., 2018). In summary, it takes more time for the driver to return to the state of natural driving, during which time it is still difficult to cope with the potential hazards that may follow. Therefore, studying the subsequent maneuvering behavior and assisting the recovery of the maneuvering behavior is a problem that must be faced to achieve L3 level human–machine co-driving, and the recovery time may be further prolonged as the automation level increases if it faces takeover, subject to deep involvement in NDRT.

4) The handover phase: This phase refers to the phase from the time point when the phase of stabilization control ends to the time point when the automatic driving is restarted. During this phase, the driver is in a stable driving state, and his/her hand control of the steering wheel involves only minor corrections, his/her foot stabilizes the position of the throttle pedal, maintains the normal speed, and after psychologically thinking that the conditions are met, he/she will restart the autonomous driving and hand over the control. Studies have evaluated trust by measuring the delay time and visual behavior of returning to the autopilot mode after disengaging from the scenario (Hergeth et al., 2015; Li et al., 2020a; Molnar et al., 2017). We use the handover period as the last phase of the takeover process, which is valuable to study drivers' psychological and behavioral trust in autonomous driving after disengaging from the scenario and potential improvement paths. In addition, defining the end point of the takeover process helps to clarify the allocation of authority and responsibility during the autopilot takeover, while restarting the autopilot mode is used as the end of the takeover-handover cycle.

### *1.4. Hypotheses and objectives of the research*

To summarize, in the current study, we investigated the effect of the auditory prompt modality on behavioral sequences in various phases of the takeover process. To better understand the time-series distribution of takeover behavior features in autonomous driving, we conducted real-vehicle experiments to verify our research hypotheses:

1) The time series in the four phases of the takeover process have

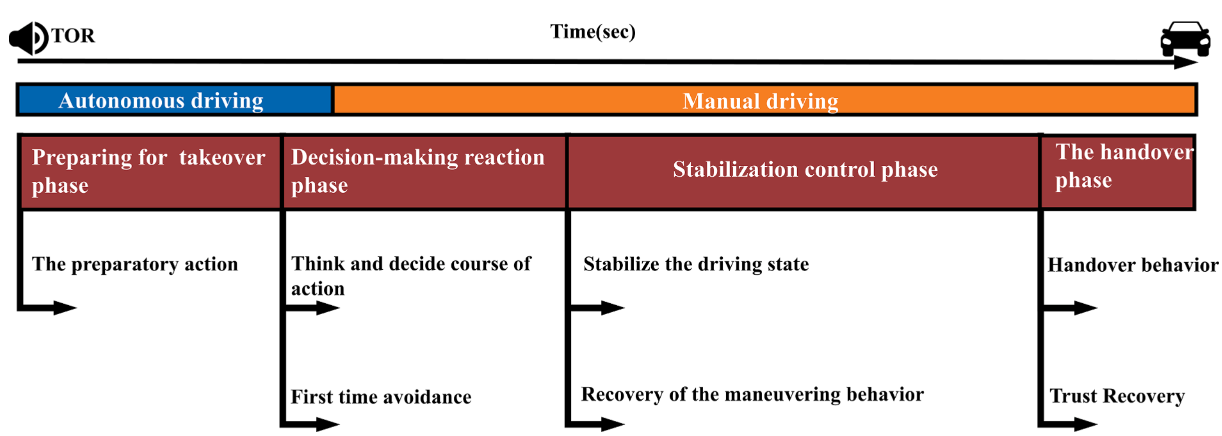


**Fig. 1.** Phase division diagram.

different behavioral and physiological and psychological characteristics, which constitute the behavioral sequence of different phases.

2) The takeover operation can be divided into different operation phases in the time series.

3) Audio types can affect the driver's behavior and performance at a temporal level.

Furthermore, this study aims to (1) verify the characteristics of different takeover phases to construct behavioral sequences through real vehicle experiments, (2) to explore the dynamic characteristic changes of the operation sequence of the takeover process, and (3) to reveal how audio types affect the driver's behavior process and driving performance at different phases. The research results will provide a dynamic design reference for the human–computer interaction design of the takeover for L3 and L4 autonomous driving.

## 2. Method

### 2.1. Participants

Participants (N = 24) were all car test drivers. They have not previously been involved in positions related to the development of autonomous driving, nor have they tested any type of autonomous vehicle, and have not been involved in similar research before. Four participants were excluded from the analysis due to missing data during testing or the inability to efficiently complete the experiment. The final sample included 20 participants (all male), ranging in age from 27 to 53 (MD = 40.9, SD = 7.75). To ensure that the participants were experienced drivers, all participants had been driving for 5 years or more and had driven more than 90,000 km per year over a five-year period (300 km of driving per day and 300 days of test driving per year). Including 1 participant with a driving age of 5 years, 5 participants with a driving age of 6–10 years, and 14 participants with a driving age of 10 years or more. All participants had normal and uncorrected vision.

Each participant received 200 CNY as compensation upon completion of the experiment. The experiment was reviewed and approved by the Biomedical Ethics Committee of Hefei University of Technology (HFUT20211111001), and its conditions met the criteria of the principles of the Declaration of Helsinki (1964) and its subsequent amendments. All participants signed an informed consent form prior to participation in the experiment.

### 2.2. Testing environment and apparatus

This experiment uses vehicle–road collaboration to simulate the driving environment of L3 autonomous driving: The driving of vehicles is controlled by an L2-level experimental vehicle, while the sensing and decision making are simulated by signals from the central tower. All vehicles and road facilities (e.g., cameras, sensors, etc.) are networked and controlled by the system from the central tower, Fig. 2 shows the composition and operation of the vehicle–road coordination system in this experiment. The vehicle–road collaboration approach ensures the participants can experience machine-controlled autonomous driving in a real traffic environment under the safety. The specific experimental environment and apparatus are as follows:

#### 2.2.1. Testing environment

The real vehicle experiments were conducted in the high-speed ring road of the test center, consisting of an elliptical track and six one-way lanes with a circumference of about 9 km. The six lanes consisted of four high-speed lanes, one self-driving lane, and one slow-speed lane. In order to present a realistic road-traffic environment to the subjects, the four non-test lanes on the high-speed loop during the non-experimental period were set up with other irrelevant vehicles (shown in Fig. 3**(b)**), and these vehicles would drive in the non-test lanes at their respective speeds (driving speed >90 Km/h).

In this experiment, the experimental section was defined as two straight lanes in an elliptical track, and a takeover scenario would be set up on each straight lane, with two experiments per lap. Before the experimental vehicle entered the takeover scenario, all irrelevant vehicles would leave the road, and the details are as shown in **2.3 Experimental design.**

#### 2.2.2. Apparatus

The vehicle used in this experiment is Cadillac Super Cruise-CT6 (such as Fig. 3), an SAE L2 class vehicle with automatic longitudinal (FSRACC full-speed adaptive cruise) and lateral (LKA road keeping assist and LCC lane following) control systems to stay on the highway throughout. The vehicle will drive in the self-driving lane at a constant speed of **60 km/h** during autonomous driving, with both longitudinal and lateral directions controlled by the system, eliminating the need for the driver to manually control the vehicle throughout without TOR. Switching from autonomous driving to manual driving mode (such as Fig. 3) can be automatically switched to manual driving by turning the steering wheel or applying the brake; while the special button on the left

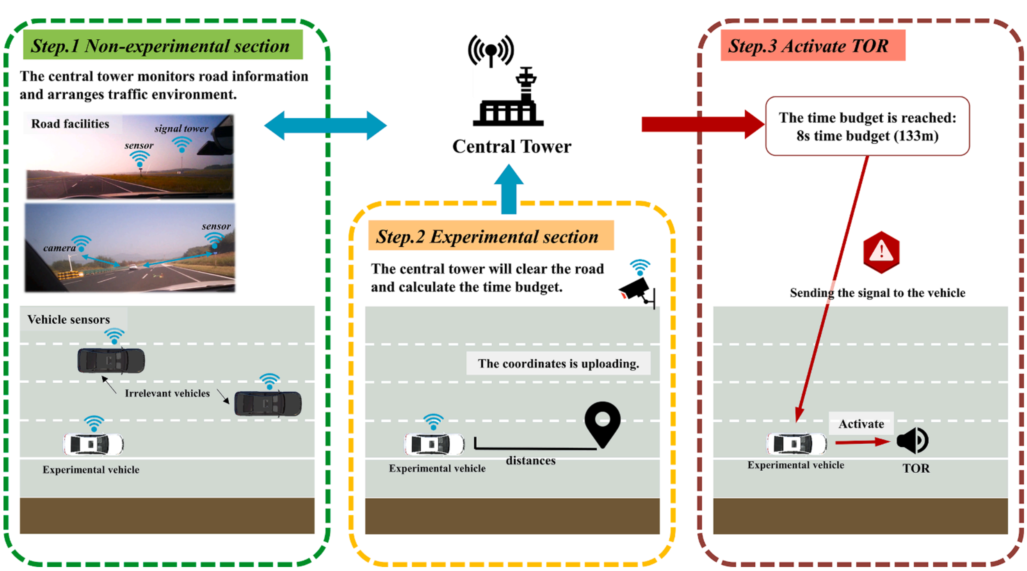


**Fig. 2.** The schematic diagram of the composition and operation of the vehicle–road collaboration system.

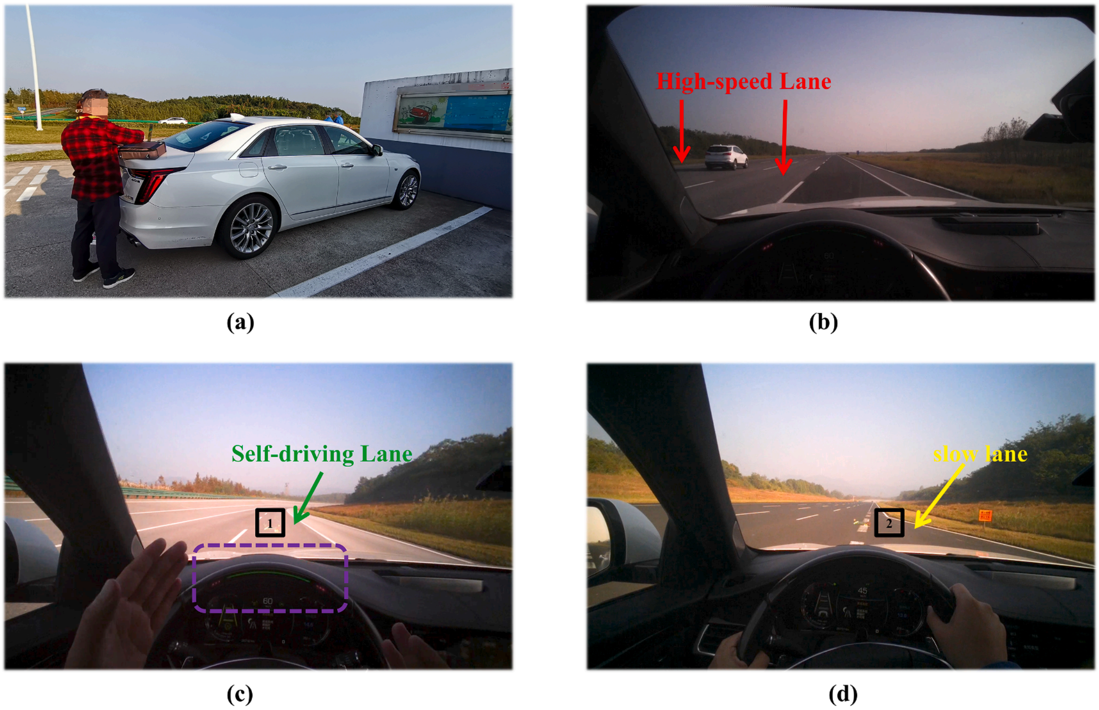


**Fig. 3.** Testing environment. (a) Cadillac Super Cruise-CT6. (b) Road traffic conditions. (c) When the automatic driving is turned on, the green light bar on the steering wheel and the 3 red LEDs on the left and right grids light up. (d) All lights on the steering wheel go out when takeover the vehicle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

side of the steering wheel needs to be pressed once when handing over the automatic driving mode; if there is no takeover within 6 s after the takeover prompt is issued or the takeover is not timely, the car will automatically stop within 10 m from the obstacle in front.

**In addition, it is important to note a change to the vehicle system**: all TOR alerts in this experiment were in the form of alerts we designed. It should be noted that the CT6′s original system, Super Cruise, has Driver Monitor (an infrared scan that automatically vibrates the seat and beeps when it detects that the driver is not paying attention to the road). Since this function is contrary to the requirement of this experiment to allow the driver to deeply engage in the NDRT and take over under different types of audio cues, we specifically disabled this function to ensure that no extraneous sounds or vibrations were emitted during the experiment.

Eye tracker: Tobii Pro Glasses 2 (head-mounted eye tracker) and Tobii Pro Lab software were used to record and observe the glance behaviors at 50 Hz.

Cameras: One camera was placed in the passenger seat to record the movements of the driver's torso, and another was placed under the driver seat to record foot movements (50 Hz).

Finally, the camera as well as the experimental vehicle data (vehicle data and central tower signals) will be recorded by a laptop connected to the CAN bus inside the vehicle.

### 2.3. *Experimental design*

This study used a fully within-subjects experimental design of 3 (TOR cues: three types of audio) * 3 (environment: three takeover scenarios). In this experiment, subjects were engaged in the NDRT in an autonomous driving car. At 8 s from the time budget of the takeover scenario (133 m), the system emits the TOR (The central tower sends the vehicle arrival signal to the on-board system of the experimental vehicle, and the on-board system automatically plays TOR after receiving the signal). Referring to the previous on-road studies, the time budget is in the range of 7 ~ 18 s (Pipkorn et al., 2022; Pipkorn et al., 2021a; Wu et al., 2021). In the pre-experiment, it was agreed that the 8 s lead time is suitable for the professional driver of this experiment, so that the driver has enough preparation time for decision making and evasion.

To ensure that subjects would not be disturbed by extraneous factors during the experiment, we cleared the road of extraneous vehicles in advance: (1) Before the experimental vehicle entered the straight lane from the curve, the security officer in the back seat would send a signal to the central tower requesting coordination of road conditions. The central tower would then clear all vehicles on the straightaway (vehicles already traveling on the straightaway would speed up and leave, and vehicles about to enter the straightaway would slow down). (2) After the driver restarted the autopilot mode, the safety officer would assess the road conditions and then send an end signal, after which the central tower would arrange for irrelevant vehicles to enter the lanes.

#### 2.3.1. *Takeover audio prompt design*

We focus on the effect of different audio prompts on the driver's behavior in the takeover scenario, and for this purpose the audio types are designed as follows:

1) **Actual sounds**: They simulate real-life sound prompts in everyday life, such as the sound of items falling. When you hear this sound, you can realize that an object has fallen.

2) **Alarm sounds**: They are sound prompts that are separated from daily life to a certain extent, and represent early warning signs in life. For example, the vehicle's buzzing warning sound indicates that the seat belt is not fastened. Based on the conclusion that the hearing sensitivity of the human ear is highest when the sound frequency is in the range of 2000 Hz to 4000 Hz, and that the warning effect is more pronounced when the base frequency of the tone is higher than that of lower frequency sounds (Lewis et al., 2018; Suzuki & Takeshima, 2004), we set the frequency of the tone to 4000 Hz.

3) **Electronic voice**: They are voice prompts that are completely different from daily life, and are virtualized AI-synthesized voices that can be distinguished. For example, you can tell that Siri, the electronic voice assistant, is the pronunciation of a virtual product, not the voice of

a real person or object.

After being produced, the above audio is played through the car speakers. We obtain more precise sound parameters at the human ear position in the in-car environment by parsing the audio recorder of the head-mounted eye tracker (The basic parameters are shown in Table. 1).

#### 2.3.2. Takeover scenario design

This experiment designed three scenarios on the classic takeover scenario combined with the current problems of autonomous driving technology. The takeover scenario contains a live build of the takeover scenario as well as audio descriptions of the takeover scenario.

*2.3.2.1. Takeover scenario building.* **Scenario 1**: “Cargo falling ahead”, designed because the foreign object on the ground is an unexpected situation, and there are countless traffic accidents caused by foreign objects falling on the highway; **Scenario 2**: “Car accident ahead”, designed because car accidents exist in various traffic scenarios, especially in the case of Japan (2018), Tesla failed to avoid the crash scene, which resulted in a secondary accident; **Scenario 3**: “Road construction ahead”, designed because many businesses use high-resolution maps for navigation. The lag in the update of the map data has caused a conflict between the high-precision map and the decision-making of the vision sensor. In order to ensure that the three experimental scenarios evade the same difficulty as well as the safety of the real-car experiment, we set the placement of the three takeover scenarios uniformly to the length of a body bit (5 m). The actual construction of the takeover scenarios is as shown in Fig. 4.

*2.3.2.2. Environmental description sound.* To ensure that the participant can correctly understand the built scenarios, the driver will automatically receive an environmental description sound recorded by a female voice when the takeover prompt is finished. The descriptions of the three takeover scenarios are all with six characters in Chinese and are processed by Adobe Audition 2021 to ensure that the sentences have the same duration. The descriptions of the takeover scenarios were unified using the vocal recording as an irrelevant variable to prevent interference with the presentation of the takeover prompt (For basic information, see Table. 2).

Finally, to prevent the driver from memorizing the roadway environment in order to prepare for the takeover in advance, a working vehicle was arranged to clean up the experimental takeover scenarios and rearrange a new takeover scenario at the indicated new coordinate location. This ensured that each time the driver took over the vehicle it was at a random location on the straightaway.

#### 2.3.3. Pre-experiment

In order to be safe and perfect for this real-vehicle experiment, we first conducted a full-process test with senior testers who have been testing autonomous driving for a long time.

(1) First, we build the takeover scenario under real roads to determine the takeover time budget as well as to evaluate whether the scenario can meet the experimental requirements.

**Table 1**
Experimental audio parameters.

| Audio type | Hz | dB |
|---|---|---|
| Actual sounds: cargo falling sound | 100 ~ 1000 | 30 ~ 75, duration 2 s |
| Actual sounds: braking sound | 1000 ~ 2500 | 60 ~ 85, duration 2 s |
| Actual sounds: construction sound | 250 ~ 1000 | 70 ~ 75, duration 2 s |
| Alarm sounds: buzzer alarm | 4000 | 70 ~ 77, duration 2 s |
| Electronic voice: “please takeover the vehicle” | 300 ~ 3400 | 60 ~ 80, duration 2 s |

(2) Subsequently, we evaluated the choice of NDRT tasks. In the pre-experiments we initially used designs from previous literature in the simulator: playing mobile games, reading articles, eating, arithmetic, texting, etc. However, in this test section environment there were foreign vehicles and the senior tester felt that the existing autopilot model was not yet 100% trusted, while the experimenter observed that the senior tester had stressful tension reactions while performing the distraction task (e.g., during frequent head lifting, hand trembling, and violently throwing away food when performing NDRT), and could not be in a distracted state for the real-world experiment, and there were great safety hazards.

As suggested, we uniformly set the NDRT to talk sideways with the experimenter in the passenger position (each conversation was required to last at least 20 s) and to do simple arithmetic (four operations within 100), and each conversation would last at least 20 s again. We reassessed the actual distraction state and performed the pre-experiment again. The results showed that the driving state of the senior testers no longer contained excessive behavior, and they recognized its safety, which was in line with the requirements of this experiment.

(3) Finally, we identified the questions to be asked to interview the drivers. These questions will assist in verifying whether their subjective reported operational behavior is consistent with the objective data:

Q1: During the takeover, did you have your left foot on the brake and your right foot on the gas pedal? (Operation error).

Q2: After taking over, under what circumstances would you choose to accelerate the vehicle? Do you think you are already safe?

### 2.4. Experiment procedure

The whole experimental process consists of three steps (shows in Fig. 5).

**Step1**: Upon arrival at the experimental site, participants were asked to read an overview information sheet about the study, followed by an explanation of the task requirements and the participant’s role in the experiment. Participants were informed that upon entering the mode of autonomous driving, they had the right to perform NDRT requested by the experimenter. Importantly, (a) participants were informed that they needed to resume manual driving when receiving the TOR, (b) participants were informed that they could only speed up by activating the automatic driving function or by stepping on the throttle pedal when they subjectively perceived it to be safe after circumventing the takeover scenario, and (c) participants were informed that they could make their own decision to hand over when they perceived it to be safe in a manual driving situation. After receiving the information, all participants signed an informed consent form and completed a demographic questionnaire.

**Step2**: After wearing the eye-tracking device, the participants manually drove to familiarize themselves with the experimental vehicle, followed by a 3-minute automated driving experience and a 2-minute TOR takeover driving experience. It is worth mentioning that the experimenter would inform the subject that the current driving environment completely simulated a highway, i.e., the subject was driving in the fast lane on the left (where extraneous vehicles moving at high speed can be observed) and the slow lane on the right side without extraneous vehicles. However, we did not tell the participants that the road would be cleared of irrelevant vehicles before issuing the TOR for this experiment. In addition, in order to obtain realistic behavioral decisions and responses, this experiment did not restrict the participant’s avoidance decision to take over (lane changing or stopping) and the direction of the lane changing after taking over.

**Step 3**: The experiment officially begins when the participant reports readiness. Starting from the entrance of the highway loop, the experiment is officially started by driving into lane 1 and turning on automatic driving. After the automatic driving mode is turned on for 10 s, the experimenter sitting in the co-pilot seat will perform the NDRT with the driver.

Before reaching the experimental section, first, the security officer

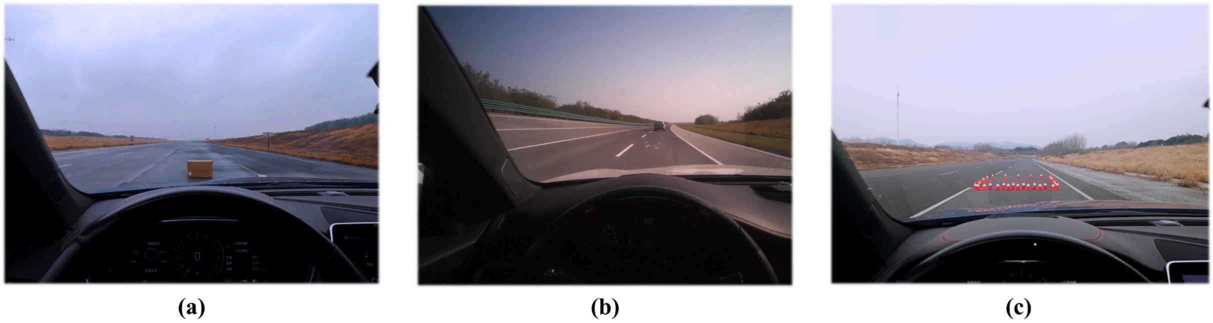


**Fig. 4.** The takeover scenarios. (a) Cargo falling ahead, (b) car accident ahead, (C) Road construction ahead.

**Table 2**
Scenario information.

| The takeover scenarios | Our way of setting up on the road | Environmental description sound (Chinese) |
|---|---|---|
| Scenario1: "cargo falling ahead" | We simulated goods falling by placing large cardboard box on the road. | 60 dB, duration 1 s |
| Scenario2: "car accident ahead" | We simulate the car accident by setting up a stopped vehicle. | 60 dB, duration 1 s |
| Scenario3: "Road construction ahead" | We simulate the construction scene by setting up construction signs and cones. | 60 dB, duration 1 s |

(sitting in the back seat) sent a signal to the tower to coordinate the road conditions. Subsequently, the experimenter would assess the driver's distraction state. When the driver showed obvious distraction (including but not limited to the appearance of the expression of hand and body movements, the increase in the number of eye contact with the experimenter, the continuous right tilt of the upper body, and the increase in self-talk), the experimenter sent a takeover prompt (as shown in Fig. 5 **(a)**). Otherwise, the takeover experiment in that section was discontinued.

After the participant reaches the fixed time budget for the takeover scenario, the system emits the takeover prompt. The participant needs to takeover the vehicle to avoid the takeover scenario. After completing the takeover scenario, the participant turns on the autopilot mode (shown in **(b), (c)** to **(d)**) When the driver thought it was safe to do so.

Participants will experience all takeover scenarios with each audio prompt, and the order of the nine experiments is completely randomized. After the participant completed all 9 experiments, he/she returns to the starting point and was interviewed by the experimenter. After the interview was completed, the experiment ended.

### 2.5. Data analysis

In this experiment, we obtained data from the bus database, eye trackers, and cameras to quantify the operating time of each action and response. The dependent variables and data types are as shown in Table. 3.

#### 2.5.1. Feature encoding and classification of behavioral sequence

In this paper, we divide four phases and construct a behavioral sequence for each phase by extracting the key features of the behavioral process common to the driver in each phase. In this experiment, we extracted the start point from TOR initiation as the time and 25 s after TOR issuance as the end point of behavioral data, and then observed these data fragments for each participant and coded the key features of the takeover process with the operation time (see Table. 4). Since the

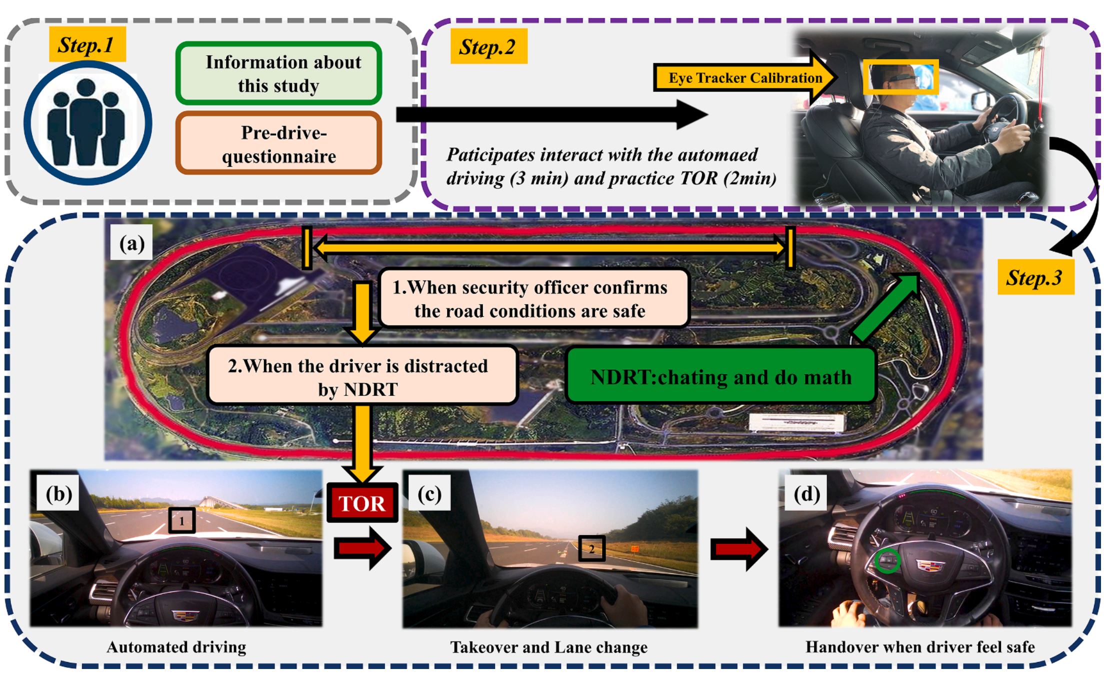


**Fig. 5.** Procedure of the experimental design.

**Table 3**
Dependent variable and desired indicator.

| *Dependent variables* | *Data sources* | *Description* |
|---|---|---|
| Eye movement indicator | Eye-tracker | Fixation time (s), Average fixation duration (s), Fixation count (counts), Pupil diameter(mm), saccade frequency (counts/s). |
| First reaction | Eye-tracker and Camera | Takeover-request (s), Hands on the wheel (s), First fixation on road(s). |
| Takeover behavior | Camera and Bus data | The type of reaction strategy, such as turning the steering wheel only or turning the steering wheel and braking. |
| Steering wheel | Bus data | Operations on the wheel (s), Steering wheel angle (deg). |
| Brake pedal | Bus data | Operations on the Brake pedal (s); Brake pedal position (%). |
| Throttle | Bus data | Operations on the throttle (s), Throttle position (%). |
| Inertial Measurement Unit | Bus data | Longitudinal acceleration ($m/s^2$), Lateral acceleration ($m/s^2$). |
| Hand in reaction | Camera and Bus data | Reactivate autonomous driving mode (s). |

handover time exceeded 25 s in only 2 out of 180 experiments, the end time was set as 25 s for the sake of uniform processing of data fragments.

Key features of the **Preparing for takeover phase**: involves The time of the first eye fixation on the road, and the time of the takeover preparation action. To identify the driver's reaction time to the TOR response, hand on the steering wheel, foot on the brake pedal, and torso behavior were coded as the takeover preparation actions.

Key features of the **Decision-making reaction phase**: involves decision behavior, and evasive maneuvers. Decision-making behavior is how the driver gains control of the vehicle, which includes whether to steer or apply the brakes first; evasive maneuvers involve the Time to operate the steering wheel for the first time, The time when the turning angle reaches the maximum angle during the first lane change, The time when the brake is pressed, and the Time to stabilize the brake.

Key features of the **Stabilization control phase**: the driver to the steering wheel is characterized by The time when the turning angle reaches the maximum angle during the secondary lane change. Since the driver does not accelerate immediately when the foot leaves the brake, for the brake pedal it is necessary to divide into: Time to release the brake, and Time to take the foot off the brake. In order to determine the driver's acceleration behavior, we use the Time for acceleration and the Time to stabilize the throttle pedal as common features.

Key features of **The handover phase**: the Time to stop steering wheel manipulation and The time to restart autonomous driving. The data of this period showed that there were still corrections to the steering wheel after the acceleration behavior ended after returning to the original lane, but the number of corrections as well as the angle did not show common features, so the stopping steering wheel rotation was uniformly used as the characteristic time point.

*2.5.2. Takeover performance of operational behavior*

Driving performance is mainly concerned with the overall driving performance of the second and third phases: maximum steering wheel angle for the first lane change, maximum steering wheel angle for the second lane change, maximum longitudinal/lateral acceleration, maximum brake pedal position percentage, and maximum throttle position percentage. The mean and standard deviation were calculated for each condition.

*2.5.3. Division of areas of interest and eye movement indicators*

Based on the fixation video recorded by the eye tracker, we observed the fixation target, classified the driver's fixation area, and divided it

**Table 4**
Coding the key features of the takeover process.

| *Feature coding* | *Description* |
|---|---|
| The time of the first eye fixation on the road | The time when the visual fixation point is first transferred to the currently driving road after the TOR is issued. |
| The time of the takeover preparation action | The time when the driver puts his/her hands on the steering wheel or makes an obvious preparation action (some drivers will raise their hands to prepare for a grasp after the TOR is issued). |
| Decision-making behavior | The time between the time the driver puts his/her hands on the steering wheel and the time the driver turns the steering wheel for the first time or applies the brakes for the first time. |
| Time to operate the steering wheel for the first time (W1) | It refers to the time when the driver turns the steering wheel for the first time after taking over the vehicle |
| The time when the turning angle reaches the maximum angle during the first lane change (W2) | It refers to the time it takes for the driver to turn the steering wheel clockwise to the maximum angle from taking over the vehicle to changing to the lane on the right |
| The time when the turning angle reaches the maximum angle during the secondary lane change (W3) | It refers to the time taken by the driver from taking over the vehicle to returning to the left lane and turning the steering wheel counterclockwise to the maximum angle |
| Time to stop steering wheel manipulation (W4) | It refers to the time taken by the driver from taking over the vehicle to the time when the steering wheel stops being turned (the positive and negative amplitudes of rotation are $< 2^\circ$). |
| The time when the brake is pressed (B1) | It refers to the time when the driver first presses the brake after taking over the vehicle |
| Time to stabilize the brake (B2) | It refers to the time from when the driver takes over the vehicle to the first time he/she stops applying the brake and keeps the brake pedal in this position |
| Time to release the brake (B3) | It refers to the time from when the driver takes over the vehicle to when the brake pedal is released for the first time. |
| Time to take the foot off the brake (B4) | It refers to the time taken by the driver from taking over the vehicle until the foot completely leaves the brake pedal. |
| Time for acceleration (T1) | It refers to the time when the driver first steps on the throttle pedal after taking over the vehicle. |
| Time to stabilize the throttle pedal (T2) | It refers to the time it takes for the driver to stabilize the throttle pedal after taking over the vehicle. |
| The time to restart autonomous driving | The driver believes that he/she is completely out of danger and can return to the autonomous driving mode, and it is the end of the takeover process. |

into 6 areas of interest (shows in Fig. 6). They are divided as follows: Left wing mirror (White), used to observe oncoming vehicles from the left rear, and the left lane is the fast lane on Chinese freeways; Dashboard (Yellow), used to observe the current status of the vehicle, such as speed, automation status; Oncoming traffic area (Red), used to observe the fast lane on the left, which is a dangerous area; Front area (Blue), used to observe the lane (lane 1) that the vehicle is currently driving on; Lane change area (Green), used to observe the area that the vehicle needs to enter when changing to the lane on the right (lane 2); Lane change observation area (Purple), used to observe the environment of the right lane change. The above six areas are all divided within 50 m in front of the vehicle (determined according to the distance line of the proving ground). The selected indicators for eye movement analysis include changes in pupil diameter, fixation time of different AOIs, fixation times,

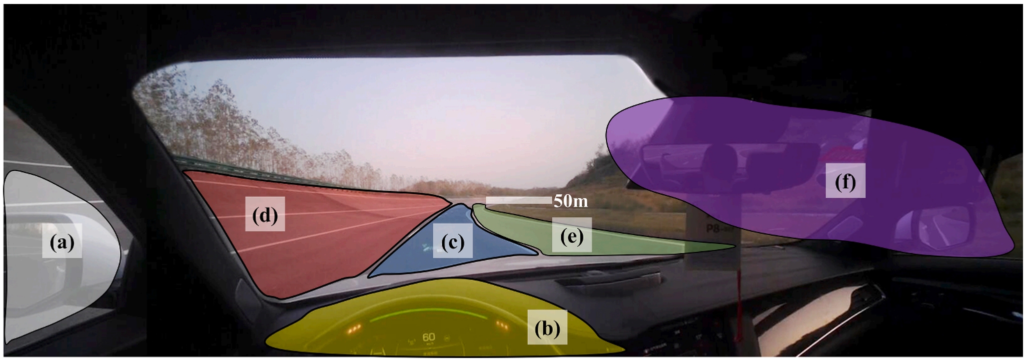


**Fig. 6.** Area of interests (AOIs). (a) Left wing mirror. (b) Dashboard. (c) Front area. (d) Oncoming area. (e) Lane change area. (f) Lane change observation area.

etc. See Table. 3 for details.

### *2.5.4. Statistical analysis*

The data were processed by software SPSS (ver.26) and Matlab (ver.2021a). Three-level (Actual sound, Alarm sound, Electronic voice) multivariate analysis of variance (MANOVA) was performed on all relevant measures. Bonferroni correction was used for multiple comparisons, and partial eta-squared ($\eta^2$) was used as a measure of effect size.

For the time series of driving operations, we mapped the feature points of each operation on the time axis and represented the probability of each operation occurring during the takeover process through Matlab dimension reduction and the computation of the time distribution of densities.

For the time series of eye movement, we did not only focus on its physiological features, but we also used the kernel density estimation algorithm to calculate the spatial distribution of eye fixation points transferred between AOIs (Comaniciu & Meer, 2002; Gershon et al., 2021). The X and Y of each participant's fixation point and time at the individual experimental level are projected into 3D space. By calculating the corresponding probability of each fixation point, we reduced the dimension to a 2D plane to obtain the change of attention degree of each region of interest during the TOR process.

## 3. Results

### *3.1. Driving behavior during the entire takeover process*

Fig. 7 shows the temporal distribution of the key features of the participants throughout the takeover. It is necessary to illustrate that Fig. 7 of **(a)**, **(b)**, **(c)**, **(d)** share the same time axis**.** In subsection **2.5.1**, we have divided each class of operational behavior into several features. In our probability visualization (d), the highlighted area indicates the time period with the highest calculated density, and the green to purple area indicates the rapidly decreasing density, i.e., the darker the color, the lower probability of the behavior occurring at that time. For any class of operation behaviors, if the highlighted areas between two features occurring successively at the same time are both highlighted areas, it is decided that the two features constitute a continuous operation, i.e., the same color in (a), (b), (c); if the highlighted areas between two features occurring successively at the same time and other colors, it is decided that the two features do not constitute a continuous operation, i.e., different colors in (a), (b), (c) in different colors. Fig. 7**(e)** records the time of key behavior initiation under the three types of audio, and we present the visual features separately from the operational features in order to facilitate the distinction.

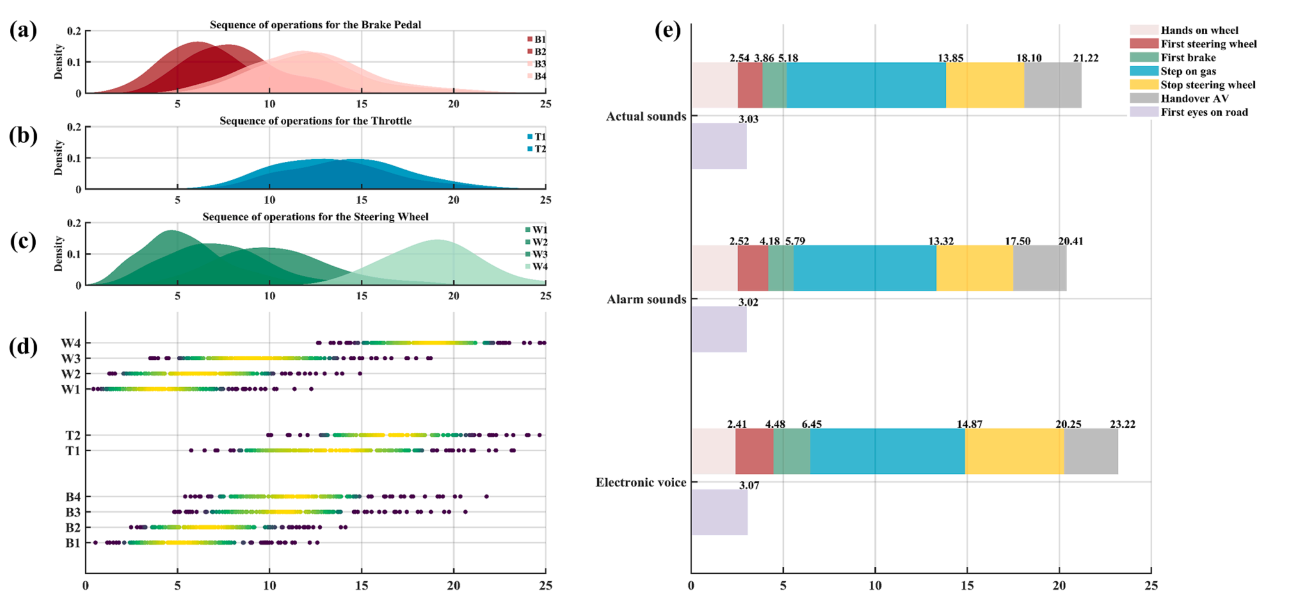


**Fig. 7.** Time distribution of key features. (a) The density distribution of the brake pedal sequence in time. (b) The density distribution of the throttle sequence in time. (c) The density distribution of the steering wheel sequence in time. (d) The density distribution of the sequence of operations. The highlighted area represents the area with a density of more than 90% at the same time phase. (e) The point in time at which critical driving behavior occurs.

*3.1.1. Preparing for takeover phase*

The results of MANOVA showed no statistical effects between three audio types on The time of the takeover preparation action ($F(2, 172) = 0.11$, $P = 0.896$, $\eta^2 = 0.001$) or The time of the first eye fixation on the road ($F(2, 172) = 0.001$, $P = 0.999$, $\eta^2 = 0.000$). The time spent by the driver to first place his or her hand on the steering wheel and the time taken to first look at the road ahead did not show a difference between the three types of audio, while the interval between these two time points was close to a constant (0.5 s). This indicates that the driver prioritizes the takeover preparation maneuver, followed by the eye gaze point moving to the road ahead (Fig. 7**(b)**).

*3.1.2. Decision-making reaction phase*

The decision reaction phase contains the first control of the steering wheel as well as the brake pedal.

**For the operation of the steering wheel:** results indicated a significant interaction effect between three audio types on the time to operating the steering wheel for the first time ($F(2, 172) = 4.468$, $p = 0.013$, $\eta^2 = 0.052$). Bonferroni Correction revealed that the actual sound (MD = 1.32 s, SD = 1.35) was significantly faster than electronic voice (MD = 2.07 s, SD = 1.68) on average by 0.75 s ($P = 0.003$). However, there was no statistical difference between actual sound and alarm sound (MD = 1.69 s, SD = 1.56) ($P = 0.084$) and there was no statistical difference between alarm sound and electronic voice difference ($P = 0.222$) (Fig. 8**(c) W1**). Furthermore, results indicated a significant interaction effect between three audio types on the time when the turning angle reaches the maximum angle during the first lane change ($F(2, 172) = 6.528$, $p = 0.002$, $\eta^2 = 0.074$). Bonferroni Correction revealed that the actual sound (MD = 3.68 s, SD = 2.72) was significantly faster than electronic voice (MD = 4.38 s, SD = 2.75) on average by 0.70 s ($P = 0.003$). And the alarm sound was significantly faster than in electronic voice (MD = 3.80 s, SD = 2.66) on average by 0.58 s ($P = 0.004$). However, there was no statistical difference between actual sound and alarm sound ($P = 0.123$) (Fig. 8**(c) W2**).

**For the operation of the brake pedal:** results indicated a highly significant interaction effect between three audio types on the time when the brake is pressed ($F(2, 172) = 5.958$, $p = 0.003$, $\eta^2 = 0.068$). Bonferroni Correction revealed that the actual sound (MD = 2.63 s, SD

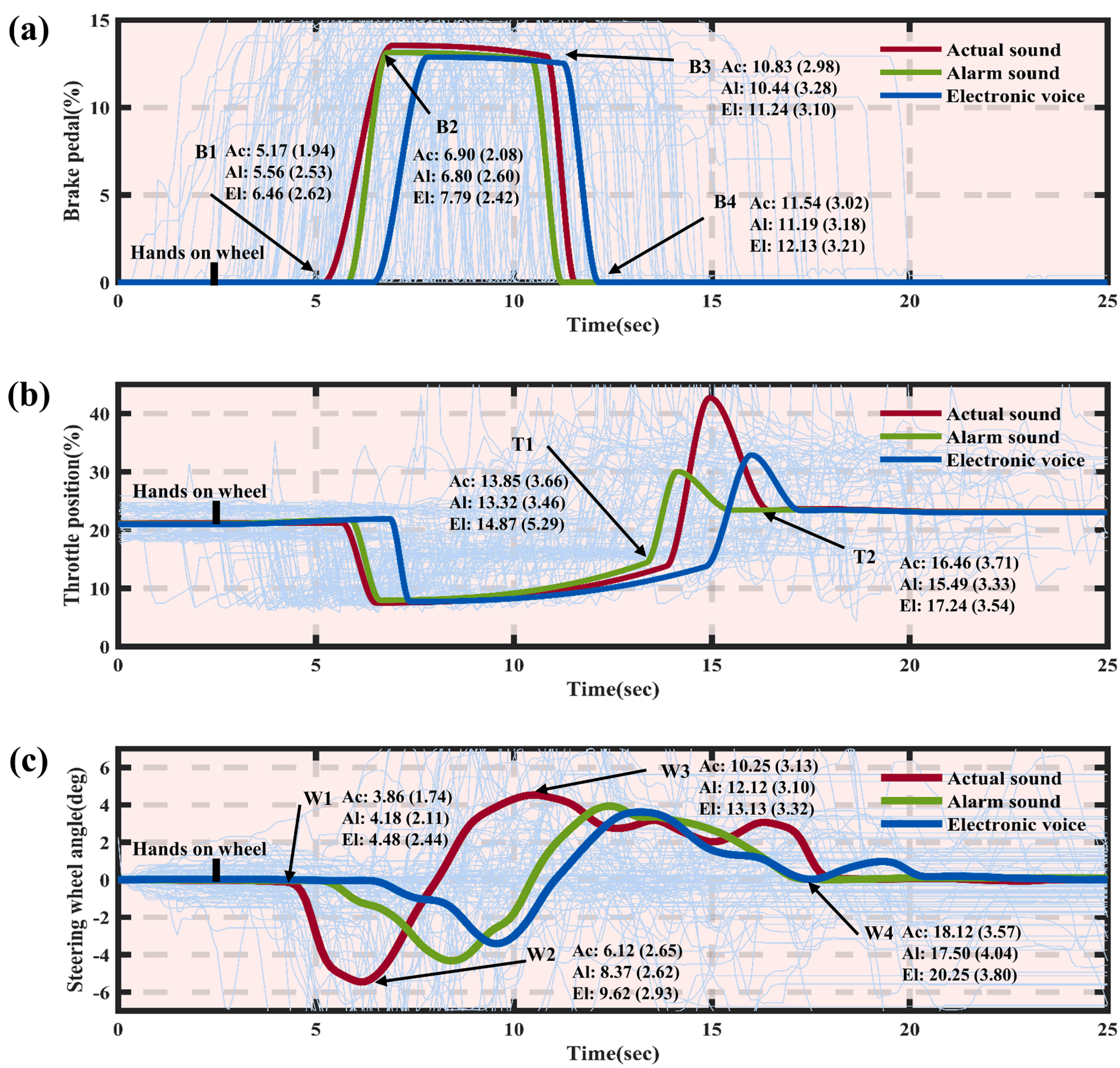


**Fig. 8.** The operations in the whole takeover process. The values show its absolute time in three audio types at each operating point (MD and SD). Plus: Ac = Actual sound, Al = Alarm sound, El = Electronic voice.

= 2.02) was highly significantly faster than electronic voice (MD = 4.05 s, SD = 2.21) on average by 1.42 s (P = 0.001), also the alarm sound (MD = 3.08 s, SD = 2.45) was significantly faster than electronic voice on average by 0.97 s (P = 0.027). However, there was no statistical difference between actual sound and alarm sound (P = 0.254) (Fig. 8**(a) B1**). Furthermore, results indicated a significant interaction effect between three audio types on the time to stabilize the brake ($F(2, 172) = 4.032$, $p = 0.013$, $\eta^2 = 0.047$). Bonferroni Correction revealed that the actual sound (MD = 4.35 s, SD = 2.15) was significantly faster than electronic voice (MD = 5.38 s, SD = 2.23) on average by 1.03 s (P = 0.018), also the alarm sound (MD = 4.30 s, SD = 2.49) was significantly faster than electronic voice on average by 1.08 s (P = 0.012). However, there was no statistical difference between actual sound and alarm sound (P = 0.876) (Fig. 7**(a) B2**).

In addition, during the decision-reaction period, statistics show that in 93.8% of cases, the driver chooses to turn the steering wheel first, and then press the brake pedal and change the lane. (In 180 experiments, the driver chose to press the brake pedal first Fig. 7**(c)**, with the same participating pressing the brake pedal first for at most twice). All drivers in this experiment chose to change to the lane on the right. This is likely due to the fact that the Chinese highways set up for this experiment have fast lanes on the left side for high-speed vehicles, while the right side is relatively safer. Even though there were no more irrelevant vehicles on the road before reaching the takeover scenario, drivers still chose the safer direction when changing the lane.

### 3.1.3. Stabilization control phase

The Stabilization control phase includes subsequent control of the steering wheel, the brake pedal, and the first control of the throttle pedal.

**For the steering wheel operation:** results indicated a highly significant interaction effect between three audio types on the time when the turning angle reaches the maximum angle during the secondary lane change ($F(2, 172) = 8.553$, $p = 0.001$, $\eta^2 = 0.094$). Bonferroni Correction revealed that the actual sound (MD = 7.43 s, SD = 2.35) was significantly faster than electronic voice (MD = 10.45 s, SD = 3.14) on average by 3.02 s ($P < 0.001$) and actual sound was significantly faster than alarm sound (MD = 9.82 s, SD = 2.94) on average by 2.39 s ($P < 0.001$). However, there was no statistical difference between alarm sound and electronic voice (P = 0.949) (Fig. 8**(c) W3**).

**For the operation of the brake pedal:** there was no significant interaction effect between three audio types on the time to release the brake (p = 0.262) and the time to take the foot off the brake (p = 0.171) (Fig. 8**(a) B3, B4**).

**For the operation of the throttle pedal:** results indicated a highly significant interaction effect between three audio types on the time for acceleration ($F(2, 172) = 4.589$, $p = 0.012$, $\eta^2 = 0.053$). Bonferroni Correction revealed that the actual sound (MD = 11.29 s, SD = 3.89) was significantly faster than electronic voice (MD = 12.46 s, SD = 5.31) (P = 0.006) on average by 1.17 s. And the alarm sound (MD = 10.85 s, SD = 3.45) was significantly faster than electronic voice on average by 1.61 s. (P = 0.015). However, there was no statistical difference between actual sound and alarm sound (P = 0.779) (Fig. 8**(b) T1**). Furthermore, results indicated a highly significant interaction effect between three audio types on the time to stabilize the throttle pedal ($F(2, 172) = 5.164$, $p = 0.007$, $\eta 2 = 0.059$). Bonferroni Correction revealed that the actual sound (MD = 14.41 s, SD = 4.27) was significantly faster than electronic voice (MD = 15.47 s, SD = 3.96) on average by 1.06 s (P = 0.041) and alarm sound (MD = 13.67 s, SD = 3.32) was highly significant faster than electronic voice on average by 1.80 s (P = 0.002). However, there was no statistical difference between actual sound and alarm sound (P = 0.257) (Fig. 8**(b) T2**).

### 3.1.4. The handover phase

Results indicated a highly significant interaction effect between three audio types on the time to stop steering wheel manipulation ($F(2, 172) = 12.034$, $p < 0.001$, $\eta^2 = 0.128$). Bonferroni Correction revealed that the actual sound (MD = 16.95 s, SD = 3.75) was significantly faster than electronic voice (MD = 18.12 s, SD = 3.57) on average by 1.17 s ($P < 0.001$). And the alarm sound (MD = 16.45 s, SD = 3.81) was significantly faster than electronic voice on average by 1.67 s ($P < 0.001$). However, there was no statistical difference between alarm sound and electronic voice (P = 0.949) (Fig. 7 **(c) W4**).

Further, results indicated no significant interaction effect between the time to stop steering wheel manipulation and the time to restart autonomous diving (p = 0.713). On average, there was a transition time (2.98 s) after the driver stopped steering, then the driver activated the autonomous driving button on the steering wheel (Fig. 7**(b)**).

### 3.1.5. The division of the driver's operation time sequence

According to the results of the density distribution diagram in Fig. 7 **(a)**, the density distribution of the time when the brake pedal is depressed is close to the time when the brake pedal is held steady. The distribution of the time of releasing the brake pedal coincides with the time of taking the foot off the brake pedal. Therefore, the chronological sequence of the actions is in a relatively coherent phase (the highlighted yellow areas coinciding in time indicates the same coherent phase). There is a significant distribution difference between the time to stabilize the brake pedal and the time to release the brake pedal (secondary green areas appear in the highlighted interval on the time distribution). Meanwhile, Fig. 8**(a)** shows that the driver has a significant period of time to hold the brake pedal.

According to the result of the probability density map Fig. 7**(a)**, the distribution between the time of stepping on the throttle pedal and the time of stabilizing the throttle pedal are coincident. Meanwhile, Fig. 8 **(b)** shows that operating the throttle pedal is a continuous process (T1 to T2).

According to the results of the probability density map Fig. 7**(c)**, the density distributions of the time of operating the steering wheel for the first time, the time of the first lane change and reaching the maximum value, and the time of the second lane change reaching the maximum value are close. There is a clear distribution difference between the above three operating actions and the time when the operation of the steering wheel is stopped. At the same time, Fig. 8**(c)** shows that after the driver completes the secondary lane change, the steering wheel still has a slight steering correction, and the magnitude is significantly smaller than that in the lane-changing behavior.

## 3.2. Visual transfer and attention in the full phase of the takeover

Fig. 9 shows the temporal distribution of participants' eye fixation point density in the six AOIs under the three types of audio. Since the time period between the preparation period and the decision-reaction period is relatively short, they are merged to facilitate the calculation of the aggregated time distribution of fixation points.

### 3.2.1. Preparing for takeover phase and Decision-making reaction phase

Three areas were first glimpsed by participants in the distracted state after TOR was issued: Front area (39.62%), Dashboard (31.45%) and Oncoming area (21.38%). Subsequently, the participant's fixation point will have the first focused period. For actual sound takeover, the appearance time of the fixation point concentration area is 3.52 ~ 5.21 s in the front area; for alarm sound takeover, the appearance time of the fixation point concentration area is 1.50 ~ 2.7 s in the front area; for electronic voice takeover, the appearance time of the fixation point concentration area is 3.63 ~ 5.36 s in the front area. In addition, the end point of the highlight zone in that time period was 7 s before in all three types of audio.

The distribution of the viewing points of **Dashboard**, **Front area**, and **Oncoming area** was higher in this phase, and the viewing area increased to 5 as time increased. Finally, there was no sample of viewing Wing mirror in this phase.

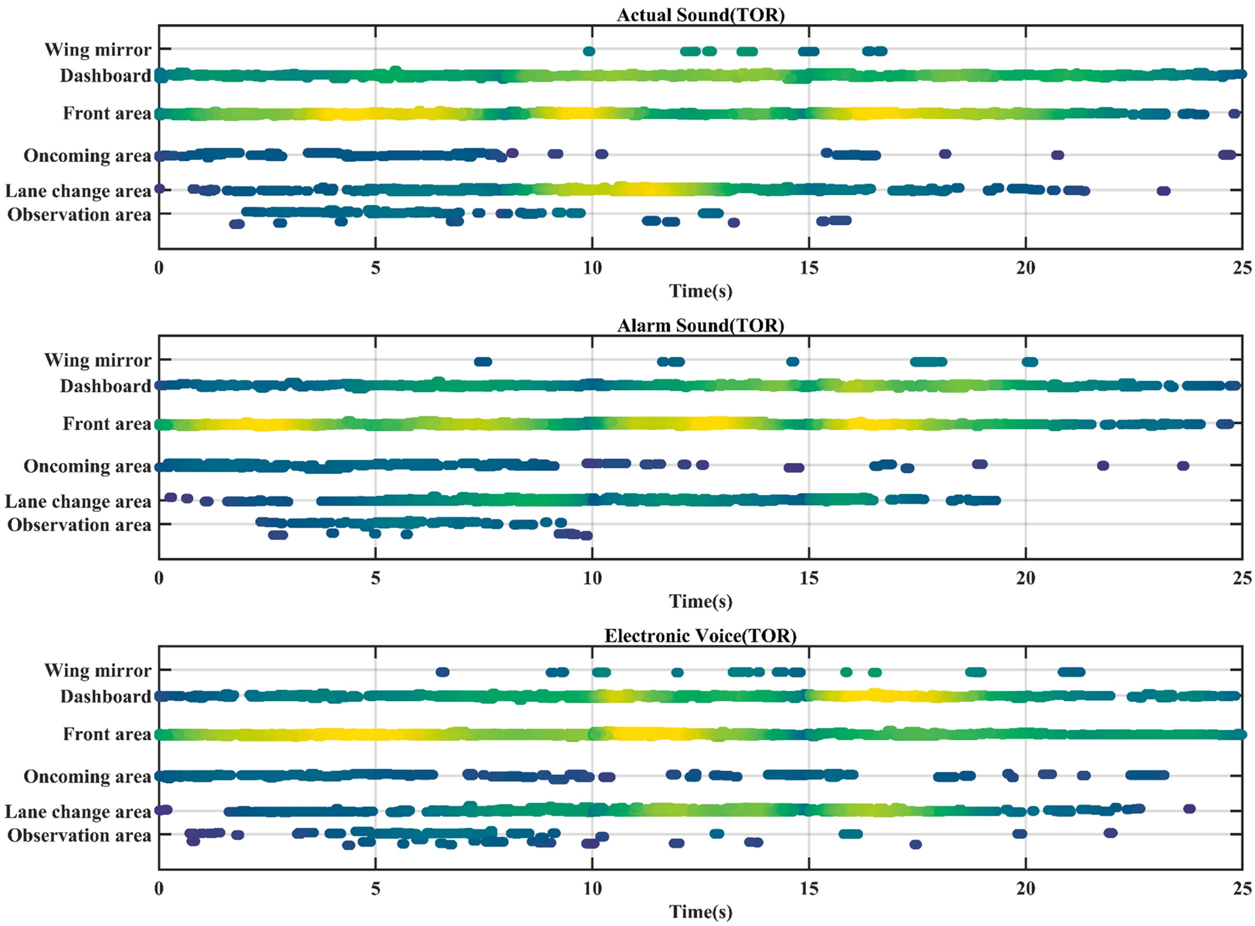


**Fig. 9.** Temporal distribution and transfer of visual attention. The darker the color, the lower the density, and the brighter the color, the higher the density. The highlighted area represents when the density is more than 90% concentrated in the same phase.

#### 3.2.2. Stabilization control phase

For actual sound takeover, the fixation point concentration area shifts to 10.75 ~ 11.56 s in the lane change area after 9.24 ~ 10.04 s in the front area (complete the secondary lane change), and then, it returns to the front area for 16.06 ~ 17.05 s (returning to the original lane and starting to accelerate); for alarm sound takeover, the time of the fixation point concentration area is 12.35 ~ 13.14 s in the front area (during the second lane change), and 15.90 ~ 16.85 s (returning to the original lane and starting to accelerate), and the transfer of the fixation point concentration area does not appear; for electronic voice takeover, the time of the fixation point concentration area is 10.43 ~ 12.11 s in the front area, which is then transferred to the dashboard for 15.96 ~ 17.47 s (returning to the original lane and starting to accelerate).

#### 3.2.3. The handover phase

Fig. 9 shows that during the handover phase, there is no fixation period. At the same time, during this period, the driver's visual behavior of viewing the areas of interest was significantly reduced, reducing to two areas: the front area and the dashboard.

In both actual sound and electronic voice takeover modes, the fixation area shifted over time in both modes, while the fixation area in actual sound takeover was only on the frontal area during the entire takeover process.

There were no statistically significant differences in mean pupil diameter and average saccade frequency among the three takeover methods throughout the entire takeover procedure. However, for the change of pupil diameter and the change of saccade frequency (we selected within ten seconds after the TOR prompt was issued), Fig. 10 shows that under the three takeover methods, the pupil diameter and the saccade frequency both increased significantly within 5 s after the TOR prompt was issued.

In addition, fixation time, fixation count, and average fixation time did not show statistical differences between different sound types.

### 3.3. Takeover performance

#### 3.3.1. Steering wheel angle for the first lane change and steering wheel angle for the second lane change

The results of our experiments show that the steering wheel angle in the first lane change is larger than in the second lane change for 76.6% of the cases (138 out of 180). Fig. 11 **(left)** illustrates that the three takeover audio types have a significant impact on the steering wheel angle during the first lane change ($F(2, 172) = 3.821$, $P = 0.024$, $\eta 2 = 0.042$). Bonferroni Correction revealed that the actual sound takeover mode (MD = 7.20 deg, SD = 5.29) was generally significantly different from the electronic voice takeover mode ($P = 0.020$). However, there is no significant difference between the actual sound and alarm sound ($P = 0.293$), or between the alarm sound takeover (MD = 5.83 deg, SD = 4.50) and electronic voice takeover (MD = 4.94 deg, SD = 3.85) ($P = 0.846$).

Fig. 11 **(right)** shows that among the three takeover audio types, there is no significant difference in steering wheel angle during secondary lane change ($F(2, 172) = 1.016$, $p = 0.348$, $\eta^2 = 0.012$). On average, under the three takeover audio types, the steering wheel angle in the second lane change is generally smaller than that in the first lane change.

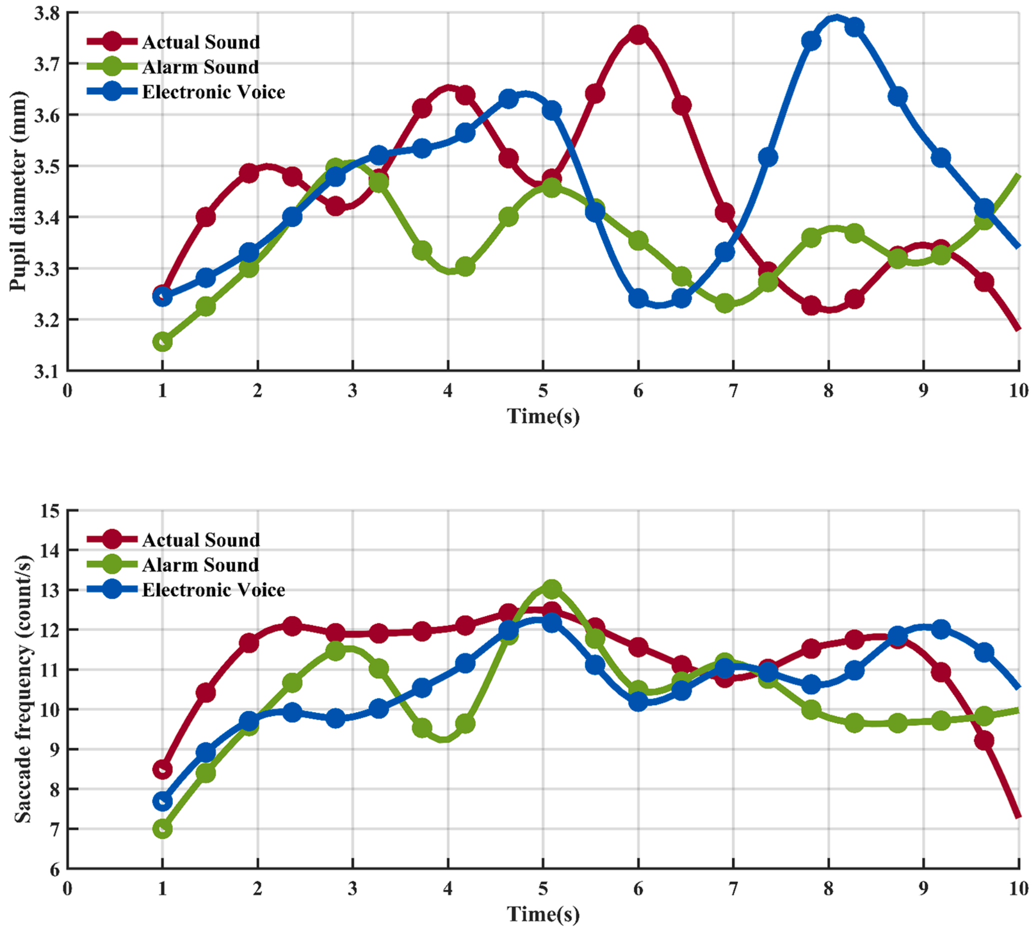


**Fig. 10.** Temporal variation of Pupil diameter and Saccade frequency.

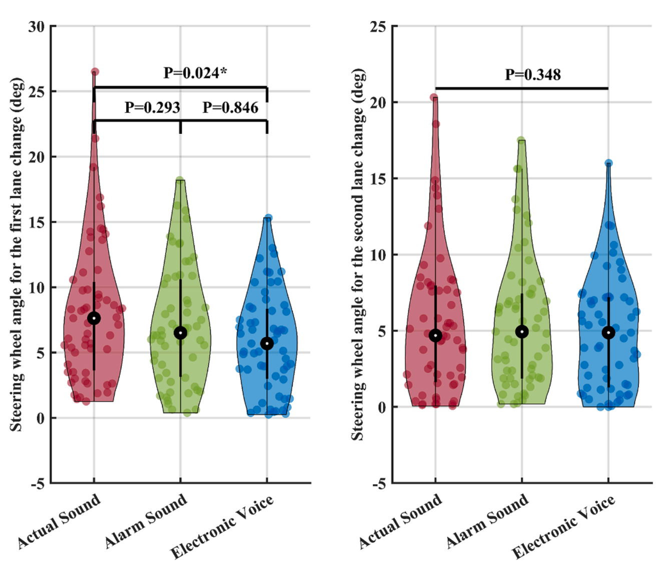


**Fig. 11.** The violinplot of steering wheel angle for the first and second lane change. Median (a white dot on the violinplot). Interquartile range (the black bar in the centre of the violin). The wider part of the violinplot represents the higher probability of the observation, the narrower part corresponds to the lower probability.

### 3.3.2. Maximum lateral and longitudinal acceleration

Fig. 12 **(left)** shows that the three takeover audio types have no significant effect on the maximum lateral acceleration ($F(2, 172) = 1.213$, $p = 0.300$, $\eta^2 = 0.014$).

Fig. 12 **(right)** shows that the three takeover audio types have a significant effect on the maximum lateral acceleration ($F(2,172) = 3.604$, $P = 0.029$, $\eta 2 = 0.042$). Bonferroni Correction revealed that the

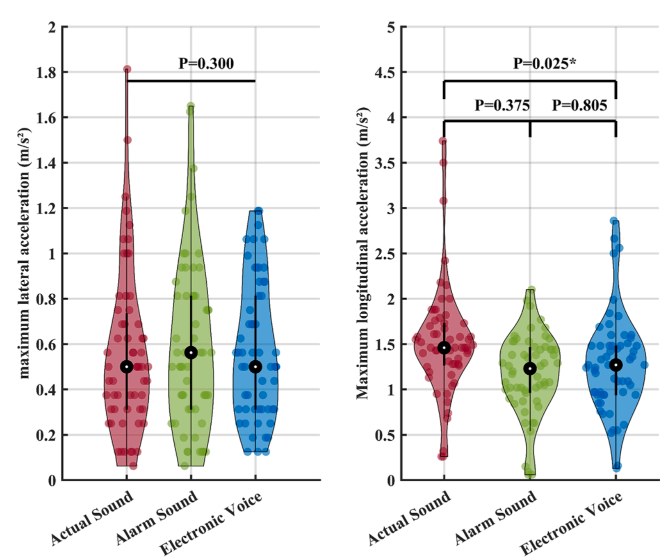


**Fig. 12.** The violinplot of maximum lateral and longitudinal acceleration. Median (a white dot on the violinplot). Interquartile range (the black bar in the centre of the violin). The wider part of the violinplot represents the higher probability of the observation, the narrower part corresponds to the lower probability.

maximum longitudinal acceleration of actual sound (MD = -1.32 $m/s^2$, SD = 0.137) was significantly greater than that of voice takeover on average by 0.70 $m/s^2$ (P = 0.025). On average, there was no significant difference in the maximum lateral acceleration between the actual sound (MD = -0.84 $m/s^2$, SD = 0.139) and alarm sound (MD = −0.62 $m/s^2$, SD = 0.138) takeover modes (P = 0.375), and the difference between the alarm sound and electronic voice takeover modes was not significant (P = 0.805).

#### 3.3.3. Maximum brake pedal position and maximum throttle position

Fig. 13 **(left)** shows that the takeover audio types have a significant effect on the maximum brake pedal position (F(2, 172) = 3.821, P = 0.024, η2 = 0.042). Bonferroni Correction revealed that in the actual sound, the maximum position of pressing the brake pedal was significantly greater than that in the electronic voice (P = 0.022), and on average, there was no difference in the maximum brake pedal position (P = 1.000) between actual sounds (MD = 13.55 %, SD = 3.04) and alarm sound (MD = 13.14 %, SD = 2.54), while the difference between alarm sound and electronic voice (MD = 12.17 %, SD = 2.13) was not significant (P = 0.184).

Fig. 13 **(right)** shows that the takeover audio types have a very significant effect on the maximum throttle pedal position (F(2, 172) = 13.221, P < 0.001, η2 = 0.138). Bonferroni Correction revealed that the maximum throttle pedal position in the actual sound was significantly different from alarm sound takeover (P < 0.001) and electronic voice (P = 0.001). In the actual sound (MD = 42.72 %, SD = 1.817), after the driver feels he/she is out of danger, the driver tends to slam the accelerator to accelerate. The difference between alarm sound (MD = 30.05 %, SD = 1.850) and electronic voice (MD = 32.89 %, SD = 1.834) was not significant (P = 0.835).

### 3.4. Post-event interviews

In interviews with the participants after the experiment, all participants reported that when they were driving an automatic vehicle, their left foot would not perform any movement, and only their right foot would operate the brake and throttle pedals (with no operational errors).

We asked participants on what occasions they would step on the throttle pedal to accelerate after taking over the vehicle. All of them reported that when they thought they were out of danger, they would press the throttle pedal to accelerate the vehicle.

When familiar with the use of the vehicle, we told the participants that they could activate the autonomous driving function and gain speed automatically by pressing a button on the steering wheel. However, experimental data showed that in the experiment, after depressing the throttle pedal to accelerate the vehicle, all participants waited for a period of time before handing over the vehicle and restarting the autonomous driving mode. This suggests that the driver will not immediately hand over the vehicle to autonomous driving even if they think they are out of danger. However, experimental data showed that in the experiment, after depressing the throttle pedal to accelerate the vehicle, all participants waited for a period of time before handing over the vehicle and restarting the autonomous driving mode. This suggests that the driver will not immediately hand over the vehicle to autonomous driving even if they think they are out of danger.

### 3.5. Behavioral sequence

Fig. 14 show the behavioral sequence of different phases.

1) Behavioral sequence of the **Preparing for takeover phase**: The driver prioritizes ending the NDRT performed, put the hands in a

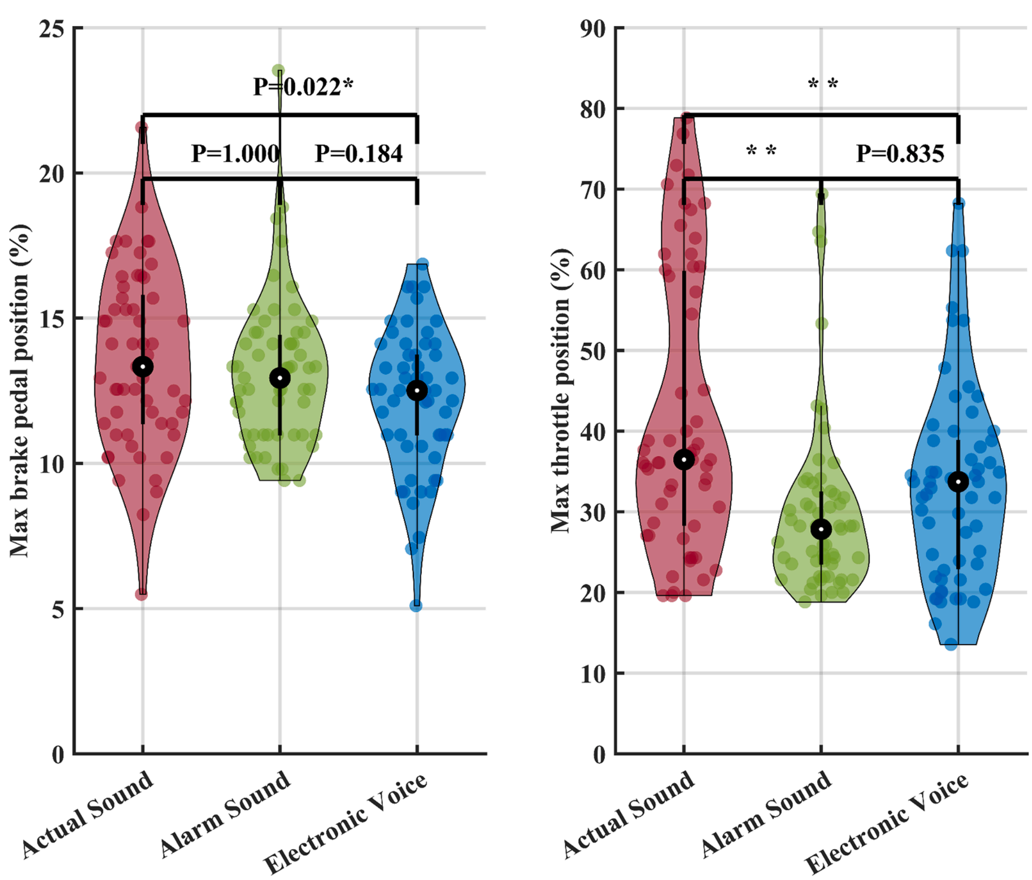


**Fig. 13.** The violinplot of maximum brake pedal position and maximum throttle position. Median (a white dot on the violinplot). Interquartile range (the black bar in the centre of the violin). The wider part of the violinplot represents the higher probability of the observation, the narrower part corresponds to the lower probability.

position that can immediately control the vehicle, and then focus on the road being driven. At this phase, the driver psychologically needs to transition from a distracted state in a non-driving task to a state ready to take back the control of the vehicle.

2) Behavioral sequence of the **Decision-making reaction phase**: After making a decision about the current environment, an avoidance operation of turning the steering wheel and then braking is made until evasion is completed.

From the perspective of driving maneuvers, the operations of decision-reaction showed significant differences under the three types of audio prompts. Among them, in terms of the time to control the steering wheel for the first time, the response speed of actual sound takeover is the fastest (3.86 s), followed by the buzzing takeover (4.17 s), and the electronic voice takeover is the slowest (4.47 s); similarly, in terms of the time to control the brake pedal for the first time, actual sound takeover showed the fastest response (5.17 s), followed by the alarm sound takeover (5.56 s), and the electronic voice was the slowest (6.45 s).

From the perspective of visual transfer, although the pupil diameter and sweep frequency under the three audio cues did not show differences brought about by the audio, all showed a significant increase within 5 s of the TOR (Fig. 10). During the transition from the start of the TOR cue to the first driving action, the first visual attention time period all appeared in the forward area and earlier than the deceleration operation, revealing that their visual attention was a contraction process: a broad scan of the surroundings shifted to focus on the currently driving road (including avoiding objects).

3) Behavioral sequence of the **Stabilization control phase**: controlling the steering wheel in the direction of the second lane change, releasing the brake pedal with the right foot, stepping on the throttle pedal with the right foot to increase the speed, and finally stabilizing the throttle pedal to maintain the normal speed. This phase is characterized not only by a shift in the operation of the driver's foot from the brake pedal to the throttle pedal, but also by frequent shifts in visual attention.

From the perspective of driving operation, although the time to release the brake did not show a difference among the three audio prompts, the secondary lane change and the control of the throttle pedal were significantly different in both the time and the performance. What's interesting here is that the start of operations in actual sound takeover mode lagged behind that of the buzzing mode.

From the perspective of visual transfer (Fig. 9), the areas of interest that drivers paid attention to during this period showed differences in the transfer under the three audio cues. Shifts in areas of interest were seen in both actual sound and electronic voice modes, while in the buzzing mode, attention was focused repeatedly on the road ahead.

4) Behavioral sequence of **The handover phase**: correction and stabilization of the steering wheel, activation of the autopilot by restarting the button after the self-perception that the conditions are met, and disengagement of the hands and feet.

The results from the section (**3.4 Post-event interviews**) show that the subjects already considered themselves to be in a safe state when they pressed the gas pedal to accelerate, however the results from the steering wheel part of the results (Fig. 8) show that the driver is still fine-tuning to correct the road after stabilizing the gas pedal, and will not press the restart button until the steering wheel has been fully stabilized for some time. Also in terms of visual transfer (Fig. 9), although the area of gaze was random and no area of concentration was observed, the area of interest started to decrease substantially and the steering wheel control was fully stabilized afterwards.

## 4. Discussion

The discussion process of this study: First, the characteristics of the behavioral sequence at different phases are explored. Then, for the operation sequence in the behavior process, this study explores the characteristic change on its time sequence. Third, study focuses on TOR's initiator-audio prompts, and reveals its global impact on behavioral processes. Finally, the differences between the simulator and the road experiment are compared.

### *4.1. Behavioral sequence characteristics of the four phases*

#### *4.1.1. Preparation for takeover phase*

Our findings suggest that the response behavior in response to TOR initiation in 93.8% of cases is to preferentially place the hand on the steering wheel and redirect the gaze to the road ahead, which is in line with previous studies (Blommer et al., 2017; Wang & Soeffker, 2018).

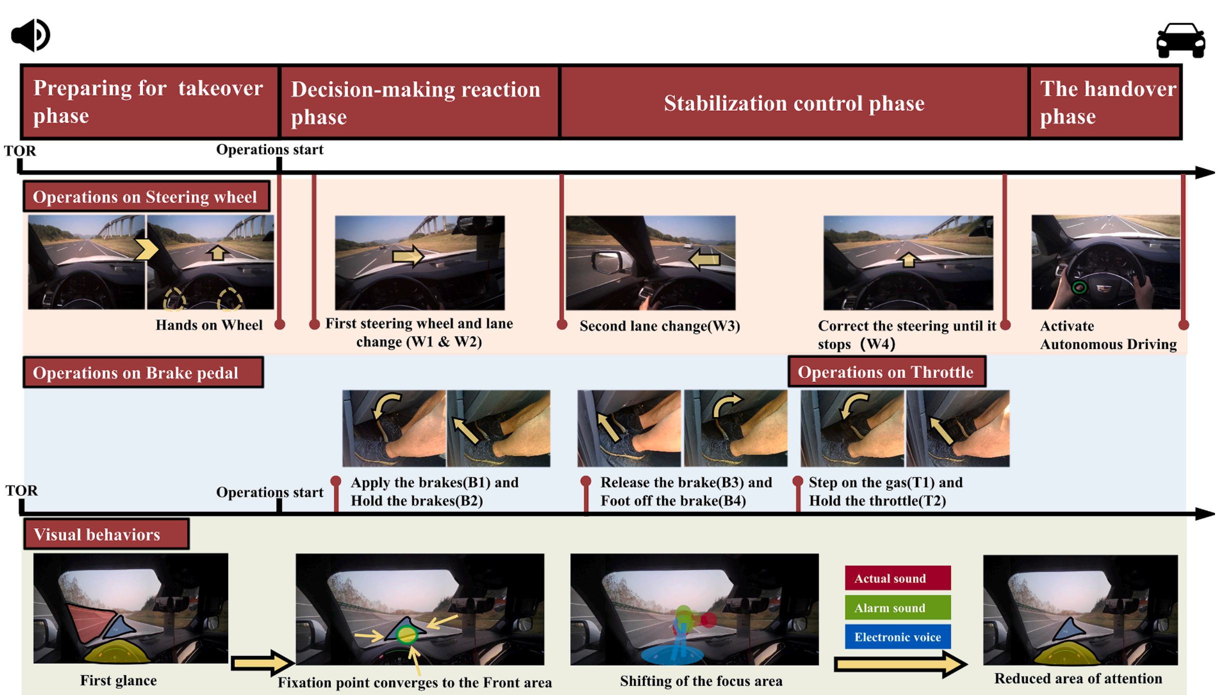


**Fig. 14.** Behavioral sequence: behavioral characteristics and operation sequences of the four phases.

We attribute the interpretation of this phenomenon to an instinctive human response. When a danger warning appears, people will instinctively hold their hands to the nearest object. This can explain why in another part of the literature (Morando et al., 2020), the phenomenon of first putting the hands on the steering wheel does not appear, because its NDRT task involves more hand manipulation. The visual response showed no difference in timing, again in line with previous recognition in the literature that eye-movement behavior in the early phases of takeover is determined by the instinctive human response (Wu et al., 2022). A comparison of the results of Pipkon et al.'s on-road experiments initiated with a TOR 9 s earlier again showed that drivers will preferentially place their hands on the steering wheel before looking at the road ahead: it takes an average of 2.70 s (Pipkorn et al., 2021b), which is very close to our result of 2.49 s. This implies that the driver's stimulus responses to TOR received in a distracted state are likely to be consistent in their temporal performance.

In summary, the response in the preparation for takeover phase is closer to the subconscious response (normal reaction to external stimuli) of a person in a sudden encounter with a danger or an unexpected situation, and does not involve decisional thinking, so the behavioral sequence does not show a temporal difference.

#### 4.1.2. Decision-making reaction phase

The ultimate goal of the decision response phase is to make the appropriate decision and complete the correct first avoidance action in a limited amount of time. Instead of taking over the vehicle immediately after the takeover preparation action, drivers prioritize searching for environmental information to make a decisional judgment. This is consistent with the conceptual model of visual, operational cognitive change from previous studies (Chen et al., 2021; Mcdonald et al., 2019; Zeeb et al., 2015). The lane change maneuver of turning the steering wheel first and then braking in our results confirms the tendency to change the lane for avoidance behavior in some simulator studies (Blommer et al., 2017; Morando et al., 2020; Wang & Soeffker, 2019).

Finally, the takeover cue is the effect on their behavior is revealed in that phase of the takeover. More importantly, this phase marks the switching of driving authority and first avoidance behavior during takeover, with significantly stronger manipulation of driving reactions than subsequent manipulations. This suggests that this period represents the period closest to danger, a transition period of operational instability specific to the switch between automated and natural driving.

#### 4.1.3. Stabilization control phase

Our results reveal the difference in operational performance of two lane changes in the decision response phase versus the stability control phase from a time-domain perspective. This supports previous studies in which there was more instability in the first lane change operation behavior (Huang & Pitts, 2022b; Li et al., 2018), that was accompanied by a significantly larger magnitude of lateral acceleration change for the first lane change than for the return (Pipkorn et al., 2022). Compared with the decision response period, the lateral maneuvering effort during the stable takeover period was significantly weaker in terms of performance (two maximum steering wheel turns). The following is our explanation for this: the decision response phase marks the switch in driving authority during the takeover and the first avoidance behavior, where the driving response is significantly stronger than in the subsequent phase of vehicle control: 1) the takeover is a switch from unconscious to conscious control of the vehicle, which causes the driver to tend to use more force to gain control. 2) the time pressure caused by the approaching hazards, i.e. the need to complete the avoidance operation in a limited amount of time (King et al., 2020), the subsequent phase of the operation is not time-pressured. Compared to the decision reaction phase, the stabilization takeover phase is less critical than the first lane change requirement in terms of both the driving environment and the urgency of the decision.

The second major characteristic of the stabilization control phase is the return to driving. We found that during this phase the driver's handling behavior increases and the effort is controlled, while the psychological perception that the hazard has been avoided accelerates the vehicle and stabilizes it to a normal state. Psychological studies suggest that it may take 40 s for the driver's psychological state to reach a stable manual driving state from the start of the takeover until the driver is in stable control of the vehicle (Kim et al., 2021), and at least 23 s for the heart rate to stabilize (Melnicuk et al., 2021), while the time to reach a stable speed was reduced by half in our results (actual sounds: 18.10 s, alarm sounds: 17.50 s, electronic voice: 20.25 s). This raises a very important issue, the stabilization control phase only partially restores the driving state and takes much longer to reach the state of natural driving, so it can only be called the phase closest to the state of natural driving.

The risk was controlled in our experiment, but real traffic is more complex and can often trigger a chain of hazards. The first avoidance does not mean that the driver has become safe, for his/her psychological and physiological state still need time to recover, which may eventually be reflected in his /her operating behavior still leading to secondary hazards. Therefore, we suggest that the research on the stability control phase should be expanded, especially the investigation of driving state recovery. Specifically, firstly, more on road studies are needed to comprehensively assess the recovery time of driving states in L3 autonomous driving situations. Second, methods that can assist in driving state recovery need to be investigated. Finally, if it is still difficult to return to a safe driving state in a short period of time after the above two efforts, then the need for autonomous vehicles to alert the driver of a timely handover at an appropriate time should be discussed.

Finally, the ultimate goal of the stability control phase is to restore the driving state, and the driver's handling behavior and performance during that phase produced varying degrees of variability, suggesting that the influence of audio cues spilled over into the subsequent takeover phase.

#### 4.1.4. The handover phase

Our results indicate the same driver preparation behavior at handover, i.e., delayed handover. Two features are shown: 1) a substantial reduction of the visual gaze area to the dashboard versus the road, and 2) a transition from a small correction of the steering wheel to full stability.

On the one hand, existing studies have shown from various perspectives that driver trust is affected as soon as the TOR is issued, and there is a certain degree of psychological recovery during the takeover process (Hergeth et al., 2015; Lee & Lee, 2022; Li et al., 2020a; Molnar et al., 2017; Seet et al., 2022), which could explain that different audio types in this experiment led to different degrees of trust recovery and thus different handover times. On the other hand, we believe that such delayed handover, even for professional drivers, due to their lack of experience with autonomous driving and their distrust of autonomous driving technology, trust their natural driving skills more after taking over, and even though they have objectively obtained information about the safety of the driving environment, they still do not psychologically believe that they should hand over to the automated driving mode immediately, but will do so only after a period of stable driving.

In summary, the behavioral process of takeover driving has a unique behavioral sequence in each of the four phases, reflecting the dynamic behavioral process (psychological and physiological, operational and performance) by which the driver completes the closed-loop process of "autonomous driving -takeover process -autonomous driving". More importantly, the effects of the first phase takeover prompt can spill over to subsequent phases and influence the timing and performance of the driving operation.

## 4.2. The time sequence of takeover operations

### 4.2.1. Time continuity of operation sequences

The takeover operations in this study are the actual control of the vehicle, corresponding to the second, third and fourth phases of the behavioral process. We split the driver's takeover operations into control of the steering wheel, the brake pedal, and the throttle pedal.

The control of the steering wheel indicates that the first phase of lateral operation performed by the driver in steering the steering wheel is to complete the first lane change and the second lane change after taking over the vehicle. The second phase is to stabilize the lateral control after the end of the lane change through continuous fine-tuning after the end of the lane change.

The control of the brake pedal indicates that the first phase of the driver's brake pedal deceleration operation is to quickly depress and stabilize the brake pedal to obtain vehicle deceleration to assist lateral lane changes, and the second phase is to release the brakes and disengage control of the brakes.

The control of the accelerator pedal showed that the driver's operation of the throttle pedal to accelerate is a continuous operation of the same phase. The driver quickly depresses the throttle pedal to the maximum value to obtain a rapid acceleration of the vehicle, then slowly lifts the accelerator and then stabilizes the throttle pedal in a natural driving range to stabilize the vehicle speed. Moreover, the continuous operation of the throttle pedal reflects the driver's psychological transition from a dangerous state to a safe state, which supports the idea that the driving operation after takeover is accompanied by psychological transformation (Chen et al., 2021). In addition, comparing the operating characteristics of the brake pedal and the throttle pedal, we find that the deceleration process shows that there is a stable braking process in the operation interval between pressing the brake and releasing the brake. However, we did not notice this phenomenon during acceleration of the throttle position curve. The above evidence shows that the driver's operation of the throttle pedal is a coherent process.

We believe that this is the empirical behavior of professional drivers and drivers with long-term driving experience. When stepping on the brakes, novice drivers are most likely to apply the brakes when encountering emergencies, resulting in sudden deceleration of the vehicle and instant vibration of the cockpit. By contrast, an experienced driver's control of the vehicle is smooth. So, when the brakes are applied, they can ensure that the vehicle remains stable after a sudden deceleration, without vibration. After releasing the brakes, the professional driver first depresses the accelerator when accelerating, reaches the maximum value of the process, and then lifts his foot slightly to stabilize the throttle pedal, so that the vehicle stabilizes its speed after the sudden acceleration. At the same time, the driver ensures the driving safety through continuous correction of the steering wheel.

### 4.2.2. Temporal association of operation and vision

After combining the occurrence times of the key operations for the three types of control mentioned above (i.e., the beginning of the operation on the steering wheel, the end of the operation on the brake pedal, and the end of the operation on the throttle pedal) and the corresponding time periods of the visual aggregation zone, we found that the takeover operation occurred either before or simultaneously with the visual aggregation time period (Table. 5). In particular, we noted that only the occurrence time of the first steering wheel operation under beeping takeover lagged behind the visual aggregation zone, while the other eight cases were consistent. We attribute this to the audio design of this experiment: 1) in section 4.1 **Behavioral sequence characteristics of the four phases**, we have verified that the audio type of warning produced a visual physiological response and differentially influenced the appearance of the visual aggregation zone (Alrefaie et al., 2019; Chen et al., 2022; Li et al., 2020b). 2) In addition, the experimental design itself was chosen to elicit the highest frequency of 4000 Hz (Lewis et al., 2017; Suzuki & Takeshima, 2004). However, even when the alarm sounds takeover, the onset of the action afterwards was still consistent with the presence of a visual aggregation zone or was briefly delayed. Thus, the high-frequency audio cues preferentially elicited changes in drivers' attention between the time of TOR issuance and the time of decision response, but their operational behavior reverted to a visual association during the stable control period. The presence of the visual aggregation area accompanied all three key maneuvering behaviors (hand from immobility to the start of steering wheel rotation, foot from downward pressure to leaving the brake, and foot from depression to stabilizing the throttle pedal).

**Table 5**
The driver's operation with the visual concentration.

| Operation type | Audio type | Absolute time(sec) | Concentration area (sec) | The association type |
|---|---|---|---|---|
| Time to operate the steering wheel [3.0 ~ 4.63] | Actual sound | 3.86 | [3.52 ~ 5.21] | Contains |
| | Alarm sound | 4.18 | [1.50 ~ 2.71] | In advance |
| | Electronic voice | 4.48 | [3.63 ~ 5.36] | Contains |
| Time to take the foot off the brake [10.12 ~ 12.13] | Actual sound | 10.83 | [10.75 ~ 11.56] | Contains |
| | Alarm sound | 10.44 | [12.35 ~ 13.14] | Delay |
| | Electronic voice | 11.24 | [10.43 ~ 12.11] | Contains |
| Time to stabilize the throttle pedal [15.40 ~ 17.74] | Actual sound | 16.46 | [16.06 ~ 17.05] | Contains |
| | Alarm sound | 15.49 | [15.90 ~ 16.85] | Delay |
| | Electronic voice | 17.24 | [15.96 ~ 17.47] | Contains |

It is an interesting finding that after a driver completes a critical maneuver, visually speaking only, his attention is also focused once. This means that the driver is associating his visual attention when completing a critical action and is consistent with the existence of a temporal interval between action and consciousness and that the action occurs before consciousness (a delay of approximately 0.2 s), which is interpreted as the brain's motor signals predating the point in time when the driver subjectively decides on the action (Miller & Schwarz, 2014; Soon et al., 2008). In summary, we propose a feasible idea: to intervene in the driver's visual focus area (warning of potential danger areas) by dynamically changing the HMI warning form (visual, auditory, tactile) before the initiation of critical operations in different takeover phases, thus optimizing the takeover behavioral sequence and finally achieving a better takeover experience and safe driving for the driver.

## 4.3. Behavioral difference

During the takeover process in this experiment, we found that the effects of the three types of audio prompts resulted not only in timing differences in takeover actions, but also in visual attention areas and takeover performance. More importantly, the impact of audio prompts not only exists in the early phases of the driver taking over, but also spreads to the subsequent takeover phases. We will decipher the reasons for this difference from the theory of human response mechanisms.

Actual sounds come from the acquired life experience, among which the sound of falling objects (low frequency and heavy pitch), braking sound (high frequency and harsh), and construction sound (frequency conversion) are the closest to the life of drivers. The figurative sound awakens the subconscious daily perception (Hoppenbrouwers et al., 2016; Onat & Büchel, 2015), causing the strongest psychological tension. Therefore, the driver's decision-making response is often faster, and his/her performance is often very strong, and the speed to return to a safe state psychologically is often lower. This also explains why, with this type of sound prompt, the driver has the fastest control over the vehicle of all audio types, but the driver's decision to accelerate the vehicle lags behind the buzzing mode. At the same time, this is why it is significantly higher than the other two audios in the first steering wheel angle, maximum longitudinal acceleration, maximum brake pedal position, and maximum throttle pedal position. Actual sound reflects a radical tendency towards takeover operations, which is in line with the results of the related studies on abstract sounds (Forster et al., 2017; Hong & Yang, 2022).

The alarm sound comes from the early warning experience (high frequency) formed through acquired life experience. Since this is a common way of alerting in life and the degree of urgency is not high (not a life-and-death game), the level of psychological tension thus induced is limited (Chen et al., 2021; Onat & Büchel, 2015). This makes the brain's decision-making lag to a certain extent, which is why the first action response of the buzzer lags behind the onomatopoeia; since the degree of generalization is limited, the induced tension is controlled, so the driver can return to a normal mental state as quickly as possible. This also explains why the visual focus in the buzzing mode is entirely on the road currently being driven on. Therefore, this is why in the buzzing prompt mode, the time of the takeover of the participants is close to the aggressiveness of the onomatopoeia (consistent with the conclusion that a high fundamental frequency can increase alertness) (Lewis et al., 2017), but the performance is close to that in the electronic voice model in terms of the performance of driving control.

The electronic voice comes from acquired non-life experiences. Humans can distinguish that the audio is a language that is different from real life. It does not give people a strong sense of priorities, and the conditioned reflex caused by fear generalization is the weakest. As a result, this results in a time lag in behavioral operations throughout the process and a gentler driving maneuver.

By reducing the driver's takeover time (Petermeijer et al., 2017a), it does not necessarily mean that subsequent takeover performance will be better (Pipkorn et al., 2021b; Wu et al., 2022; Zeeb et al., 2015). In contrast to previous perceptions, in experiments with actual sounds, although avoidance was possible at a distance from the hazard, the behavior was aggressive and potentially dangerous; in experiments with electronic voices, drivers performed more restrained avoidance behavior as the vehicle approached the hazard. We suggest that the intensity of the conditioned reflexes elicited influences the difference in decision time, with longer decision times helping drivers to fully understand the current environmental information and plan their decision behavior, while shorter decision times allow for effective decision making in general directions (e.g., changing lanes, stopping) with limited information, but make it difficult to plan for details (e.g., Manipulation strength, angle). Our results also do not support measuring takeover performance solely by takeover time and some initial performance: audio that elicits a faster takeover response may tend to favor more intense maneuvering behavior and longer psychological recovery, while audio that elicits a slower takeover response instead contributes to smoother vehicle control.

In summary, we recommend that the HMI system choose different audio prompts for different situations or levels of crisis. For example, in the case of threatening the life of the driver, we should choose the prompts of actual sounds, which helps the driver to make a quick decision-making response; in relatively safe occasions, we should choose electronic voice prompts to help reduce extreme takeover operations; and to help with early warning and to restore driving psychology, we can use alarm sound prompts. A selection of different types of audio prompts can help improve the driving experience and realize safe driving while helping the driver avoid risks.

### 4.4. Compare the difference between simulator and on-road studies

#### 4.4.1. Differences in takeover behavior

Similar decision-making behaviors were observed in both simulator and road studies. While the previous driving perception was "braking first in case of danger", in autonomous driving, drivers tend to evade by turning the steering wheel first and then braking. Not only is this supported by simulation studies (Blommer et al., 2017; Morando et al., 2020; Wang & Soeffker, 2019), but real-world road verification of this behavior has also been obtained from professional drivers in this study, and the same phenomenon has been observed in recent real-road experiments (Pipkorn et al., 2022; Wu et al., 2021).

We argue that this convergent behavior is common under short takeover lead times. In this case, drivers need to make avoidance actions in a limited time after receiving the TOR, although road experiments will ensure safety, while under the long takeover lead time, for example, 18 s, drivers can learn about the takeover event earlier and can slow down earlier to achieve better lateral control (Pipkorn et al., 2022). Of course, further reducing the lead time (below 5 s), although braking before steering has been observed in simulator studies (Wu et al., 2022), the danger is almost unavoidable in terms of the time required for the decision-making behavior in this paper and in the on road study described above. We believe that the confirmation of perfect takeover lead time requires more on road studies: in this experiment, for example, for an autonomous vehicle driving at 60Km/h, a lead time of 8 s requires a forward detection distance of more than 133 m, which is far beyond the detection distance of sensors. A longer lead time means a longer detection radius and more complex machine decisions, which requires excessive R&D costs for a single vehicle to achieve full autonomous driving. Therefore, we suggest that smart transportation infrastructure should be built to support the research and development of autonomous driving.

#### 4.4.2. Differences in takeover time

The timing of the onset of takeover behavior is generally faster for simulators than for on road studies. According to the prediction model in the review by Mcdonald et al., the takeover time was 3.31 s when the takeover lead time was 8 s (Mcdonald et al., 2019). In addition, by comparing simulator experiments with similar takeover lead times, it was found that the average takeover time was mostly below 2.8 s (Wang et al., 2022; Wu et al., 2022). However, the times for our first operations were all on the large side (actual sounds: 3.86 s, alarm sounds: 4.18 s, electronic voice: 4.48 s). The results of these comparisons of takeover times will be explained in terms of:

1) The TOR of this experiment involved three types of prompts: the prompts caused different levels of effects on driver takeover time and visual evidence showed a physiological response in drivers' visual behavior after receiving the audio cues, consistent with what has been observed in previous literature (Alrefaie et al., 2019; Chen et al., 2022; Li et al., 2020b), further demonstrating the effectiveness of the effect of takeover cue tones on driver decision-making behavior.

2) The simulator study simplifies the complex driving environment in reality: the real driving environment is more complex compared with those in simulator studies, and more time is needed to make the right decision after aborting the NDRT. Comparing with the real vehicle study: the average takeover time was between 3.43 and 3.69 for the same takeover lead time (Sahai et al., 2021); with a 9 s takeover lead time, the average takeover time was 4.4 s (Pipkorn et al., 2022) slightly later than our results and in agreement with the results for electronic speech among the three audio types. In addition, Pipkorn et al. (2022) pointed out that the prediction models of existing studies for takeover time were based on linear models for short takeover and did not match the prediction of takeover time for long lead times.

Finally, we do not support the takeover time model in the current study, and the relationship between takeover lead time and takeover time is not simply linear, and there is an effect of TOR warning factor. In addition, realistic driving conditions can lead to longer takeover times, so the takeover times for the simulator experiments need to be reassessed on realistic roads. It is important to recognize that the occupational background of the subjects in this paper results in their ability to control the vehicle and take over the driving recovery beyond that of the majority of the general population. Therefore, the takeover time budget for an average person should be reconsidered, the TOR needs to be presented in a form that is determined by the level of criticality, and the recovery from driving in the subsequent stages of the takeover may require human–computer interaction, otherwise it is not safe to take over the vehicle.

#### *4.4.3. Differences in takeover performance*

In terms of the strength of manipulation of takeover behavior, simulators are generally larger than on road studies. In the takeover performance results of simulator studies, the maximum longitudinal/lateral acceleration was 3.67 and 3.65 $m/s^2$ (Wang et al., 2022), the maximum deceleration reached $-7.35$ $m/s^2$(Wu et al., 2022), the average acceleration was also over 6 $m/s^2$ (Gold et al., 2013). In contrast, in the on road study, the results of this paper are similar to those of Pipkorn et al. in that none of the takeover performance showed excessive values (Pipkorn et al., 2022). This suggests that the simulator study may differ significantly from the road study in terms of the values of the manipulation effort.

Taken together, this section shows that simulator studies can still inform and model takeover behavior, but the validity of the timing of takeover behavior and the strength of manipulation should be tested by on-road research. We believe that the advantages of simulators cannot be ignored, and that on road studies are, after all, experiments conducted in a secure environment (subject to many safety restrictions), so many experimental studies involving hazards still require simulator participation as a priority.

### *4.5. Limitations and future work*

The results of this paper are based on road experiments with real vehicles. This experiment provides a higher degree of realism than simulator studies in some literature. We simulated the real traffic environment on the test road, however, due to ethical and safety considerations, it is impossible for us to perform real-life scene destruction on the public road to prevent the autonomous vehicle from actually crashing during the test. Also for safety reasons, we unified the form of NDRT tasks into conversations. This also provides a feasible form of engaging in NDRT tasks in current real autonomous driving experiments. At the same time, we hope to add NDRT forms that are more suitable for advanced autonomous driving in the follow-up real vehicle experiments. In addition, all participants have not participated in the development and test drive experience of autonomous vehicles. But because they are professional drivers, the consistency of their takeovers and their decision-making judgments may not necessarily be representative of the general population.

To understand how the current results can be generalized to more realistic settings and wider populations, in the future, the researchers will expand and refine the behavioral sequence based on the data of more professional drivers and ordinary drivers, and study behavior optimization strategies with application value according to different takeover phases. This is expected to provide dynamic human–computer interaction design.

## 5. Conclusion

The main contribution of this study is to divide the four phases of the behavioral process of takeover driving from a temporal perspective, and investigate the influence of different audio types of takeover prompts on the behavioral process (visual behavior, sequence of operations) of taking over autonomous driving. The following conclusions can be drawn:

(i): There are unique behavioral characteristics in the four phases, which reveal that the takeover of autonomous driving is a dynamic behavioral sequence. More importantly, the effects of the takeover prompts in the first phase will be carried over in subsequent phases.

(ii): The time sequence of takeover operations has coherent and incoherent dynamic characteristics, and the visual attention gathering accompanies the operation behavior, which is helpful for the design of human–computer interaction at the operational level of different takeover phases.

(iii): Different types of audio prompts will affect the timing of the takeover operation and its driving performance. Choosing different audio prompts or combinations can help improve the effect of taking over the vehicle.

Future research will provide human–computer interaction design from the perspective of the entire takeover process to optimize driving behavior, and guide follow-up research to determine the most appropriate mode of audio prompts and optimization of takeover actions. This can ultimately help improve the autonomous driving experience as well as traffic safety.

## CRediT authorship contribution statement

**Zhenhua Yu:** Conceptualization, Data curation, Methodology, Writing – review & editing. **Gerui Xu:** Conceptualization, Investigation, Data curation, Data analysis, Writing – original draft, Writing – review & editing. **Kang Jiang:** Conceptualization, Investigation, Data analysis, Writing – review & editing. **Zhongxiang Feng:** Conceptualization, Writing – review & editing, Supervision. **Shan Xu:** Conceptualization, Methodology.

## 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

Data will be made available on request.

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