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Beyond Beeps: Evaluating Soundscapes for Take-Over Situations in Automated Vehicles

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ABSTRACT
In automated vehicles, beeps are widely used as alarms and feedback. However, as automation advances, there is a need to explore subtler, contextually sound-based notifications for non-urgent situations. While auditory interfaces for take-over requests have been studied, limited attention has been given to using soundscapes for such alerts. This paper designed and evaluated soundscapes using existing driving-related sounds – amplified road noise and/or dimmed background music – for scheduled take-over situations. A driving simulator study showed that these soundscapes enhanced reaction time, situation awareness, and acceptance without causing annoyance. Particularly, the combined condition (music dimming and road noise amplifying) supported higher driver awareness and responsiveness. These findings suggest that soundscapes can offer safer, more intuitive take-over alerts by embedding information into familiar audio cues. This study contributes to developing soundscapes as novel alert mechanisms that integrate seamlessly with the driving environment to enhance both safety and user experience in automated vehicles.

KEYWORDS
Automated vehicles; soundscape; sound design; human-machine interaction

1. Introduction

Sounds enable humans to perceive environmental changes, acting as affordances (Kaptelinin & Nardi, 2012) that influence behavioural changes. Sound affordance is a perceived opportunity for action within an environment characterized by changes that humans perceive and associate with specific sounds (Kari et al., 2021). These affordances can be contextually bound, allowing humans to perceive changes in their surroundings or situation through variations in sound. This study explores the potential of soundscapes with natural signals as sound affordances. A preferred way to design interactions for the future of everyday life is to use richer, more informative, less intrusive signals, which Norman (1995) refers to as natural signals. Natural signals provide information in a non-intrusive way, being natural, non-disturbing, and constantly aware of events around humans. For example, humans can perceive boiling water by its sound. Sound naturally conveys rich pictures of what happens around humans because it is an automatic result whenever objects move, scrape, or resist. This process happens so automatically and naturally that humans are often unaware of how much their sense of space and their knowledge of surrounding events depend on sounds (Norman, 2009). Sounds can serve as implicit communication (Castelfranchi, 1995). For example, while driving, a driver's attention might be focused

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on the road, radio, or passengers rather than on the noise of the engine or the road. However, when a strange noise is detected, the driver's attention is quickly attracted to the noise.

In the context of automated vehicles, one of the critical challenges in interaction research is the design of the take-over situation, with an estimated over 200 articles published on the topic (de Winter et al., 2021). Until automated driving systems can consistently manage all driving tasks in diverse road conditions (SAE International, 2021), drivers must take control when driving automation fails or reaches its operational limits. Ensuring traffic safety necessitates timely and proficient driver responses to take-over requests for appropriate task takeovers (Gold et al., 2013). A take-over request is a warning provided by the vehicle when it recognizes it cannot handle a traffic situation. Research on take-over requests has primarily focused on SAE Level 3 conditionally automated vehicles (Eriksson & Stanton, 2017), which require drivers to be "fall-back ready" for emergency transitions. Therefore, take-over requests that facilitate rapid control transition to manual driving have been widely investigated. Consequently, auditory signals like beeps or speech-based alerts have been commonly employed for notifications or to convey urgency. However, transitions do not always occur under urgent circumstances (Rydström et al., 2023). Higher levels of driving automation, such as SAE Level 4, offer broader operational design domains, allowing vehicles to anticipate when they are approaching their operational limits and request takeovers in advance. These scheduled takeovers allow for more sufficient time budgets (Gold et al., 2018) prior to the system limit. As such, take-over request design can extend beyond the immediate goal of minimizing response time to also consider human factors like driver experience.

This study aims to evaluate the effects of soundscapes for alerting take-over situations. We designed soundscapes and conducted a within-subject study with twenty-four participants in a driving simulator for highly automated vehicles. We tested in scheduled take-over situations, with ample time to take over where soundscapes are expected to serve as pre-warnings, allowing drivers to recognize the upcoming transition and prompting psychological and behavioural adjustments. We used background sounds during driving, i.e., road noise and background music, as natural signals and evaluated the potential of these soundscapes to implicitly communicate scheduled take-over situations. This evaluation was based on both objective behaviour (take-over reaction time and eye-gaze behaviour) and subjective assessment (situation awareness, workload, acceptance, perceived urgency, and preference ranking). Despite extensive research on take-over requests, prior work has mainly focused on urgent alerts, often leading to driver annoyance, using explicit signals such as beeps or speech, and little attention has been paid to the use of ambient, non-intrusive auditory signals. We selected background music and road noise because these are already part of the natural driving environment. As such, their subtle modulation is expected to serve as an implicit cue to gradually reorient the driver's attention, avoiding the annoyance sometimes associated with artificial alerts. While many designs focus on creating new sounds, we propose interfaces that amplify (road noise amplification) or diminish (music dimming) existing soundscapes to convey information about upcoming transition situations.

2. Related works

2.1. Take-over requests in automated vehicle

The majority of studies on take-over requests (TORs) in automated vehicles have focused on the timing and modality of the warning design. For example, Gold et al. (2013) demonstrated that alerts triggered 7s before an incident resulted in safer handovers than those presented 5s before. Several studies have explored various TOR formats, highlighting a general preference among drivers for auditory signals to enhance alert effectiveness, such as decreasing reaction time (Naujoks et al., 2021; Petermeijer et al., 2017; Politis et al., 2015). This preference is especially relevant in higher driving automation, where drivers can perform secondary tasks. In such scenarios, the omnidirectional nature of auditory signals makes them effective for capturing attention, regardless of where drivers are looking (Siwiak & Jame, 2009). While the use of sound is effective in prompting driver attention, the specific acoustic characteristics of auditory signals affect how they are perceived. Higher sound frequencies, faster pulse rates, and louder volumes are known to increase perceived urgency (Ho & Spence, 2005), making sound more attention-grabbing. However, such high urgency levels can also lead to increased discomfort

(Özcan & Egmond, 2012). For example, Hu and Hu (2024) found that takeover requests with shorter inter-pulse intervals were perceived as more urgent but also resulted in higher stress levels.

Given the expansion of research into higher levels of driving automation, there has been a growing interest in non-critical driving scenarios and scheduled take-over interactions (Rydström et al., 2023; Zhang et al., 2019). In addition, when drivers engage in non-driving-related tasks during Level 3 or higher automated driving, previous studies have worked on developing user interfaces that aid in suspending non-driving-related tasks and facilitating situation awareness. This includes examining the modality of TORs and the devices used to deliver them, where a multi-stage warning procedure (Winkler et al., 2016) has been suggested to support situation awareness. For example, Hasegawa et al. (2024) showed that a two-stage transition improves take-over performance and enhances situation awareness in scheduled take-over situations. In a two-stage transition, the first stage, referred to as pre-alert, gently directs drivers' attention to the surrounding environment without requiring immediate control. This provides time to prepare for the takeover mentally and physically. In the second stage, a more direct alert prompts drivers to assume complete vehicle control. Previous studies have shown that pre-alerts can improve situation awareness (Lu et al., 2017; 2019; Xu et al., 2022). In addition, Ma et al. (2021) found that drivers showed lower physiological stress, better takeover performance, and higher acceptance with a two-stage transition warning compared to a single-stage transition warning. They suggested that such a two-stage transition warning holds promise for enhancing takeover safety in future connected vehicles. Moreover, van der Heiden et al. (2017) examined the effect of pre-alerts and found that providing an auditory pulse (beep) pre-alert 20 s before the system limit led to safer transitions. However, the use of pulse tones also induced driver annoyance.

In high levels of driving automation (i.e., SAE Level 3 or 4), drivers are likely to engage in non-driving-related tasks, such as phoning or reading, making it more likely that their gaze will be directed away from the road. In such scenarios, capturing drivers' attention broadly becomes crucial and capturing omnidirectional attention is an advantage of auditory interfaces (Siwiak & Jame, 2009). However, while sound can draw the drivers' attention regardless of their visual attention (Liu, 2001), previous studies have predominantly used high-intensity alerts, such as beeps, to prompt rapid responses, often leading to driver annoyance (Roche & Brandenburg, 2018; van der Heiden et al., 2017). In the context of scheduled take-over situations, where urgency is low but increasing drivers' situation awareness is needed, there is a need to design and evaluate more subtle auditory interfaces. These should leverage the benefits of sound without causing irritation, fitting the unique context of non-emergency, scheduled take-over situations.

2.2. Soundscape design

A soundscape is an auditory environment perceived by individuals in a given context (Murray, 1976). It is created through human perception of the surrounding acoustic environment and conveys contextual information (Aletta et al., 2016). Ambient sounds are background sounds that form part of the soundscape. Ambient systems provide information within the user's attention periphery (Matviienko et al., 2015). Gradually changing the level of ambient stimuli can stimulate human perception and trigger awareness of new situations. Studies of ambient light in automated vehicles (el Jouhri et al., 2023; Feierle et al., 2020; Yang et al., 2017), such as changing colours according to automation modes or providing transition information, have already been conducted and showed that the ambient light improved driver behaviour, such as takeover time and road gaze duration. However, there is a paucity of research on ambient sound in automated vehicles. While Bazilinskyy et al. (2019) evaluated continuous feedback on Advanced Driver Assistance Systems (ADAS) functions, there are no studies on take-over situations to the best of our knowledge.

When auditory signals represent quantitative data, the process is known as "sonification" (Nees & Walker, 2011). In warning systems, the properties of sounds are modulated based on driving situations. For example, parking sensors use auditory signals that increase in pulse rate as the vehicle approaches a parked vehicle, creating a heightened sense of urgency (van den Beukel et al., 2016; van der Heiden et al., 2017). Gray (2011) found that a looming auditory collision warning, which increases in intensity, reduces brake response times compared to a non-looming warning. Applying sonification to ambient sounds can be used to inform drivers about an approaching transition, allowing the sense of urgency to increase gradually as the transition draws near. While explicit sounds like beeps provide direct information about the transition scenario, ambient sounds with sonification are expected to support drivers in entering the transition phase progressively.

2.3. Driving noise and background music in driving

Driving noise, commonly referred to as "everyday listening" (Gaver, 1993) in driving, is typically considered as "noise," and vehicle designers work to reduce driving noise to achieve high comfort levels and to shape noise in accordance with brand and vehicle type. However, drivers can extract information about vehicles and road events through driving noise (Gang et al., 2018), and changes in driving noise can also affect driving behaviours such as speed choice (Wang & Wang, 2012). When drivers notice changes in driving noise, such as engine ticking, road friction, or passing vehicle sounds, they instinctively pay attention to the underlying causes. Therefore, the source of everyday listening in the driving context, which drivers are already accustomed to recognising as a source of information, has the potential to draw drivers' attention. This means that driving noise can be seen as a natural signal for implicit communication. With advancements in NVH (Noise, Vibration, and Harshness) technology, driving noise can be actively controlled (Sobieszczanski-Sobieski et al., 2001). Active noise control systems effectively reduce overall noise levels by emitting inverted sound waves to incoming noise, resulting in a quieter ride (Bein et al., 2012). Think differently; noise can also be intentionally exposed.

Music is commonly used as background sound in drivers' driving environments. Most drivers listen to music while driving, and intend to do this even more with higher automation levels (Kyriakidis et al., 2015; Sloboda et al., 2001), with only a minority driving in silence (Dibben & Williamson, 2007). Previous research on the effects of music stimuli on driving behaviour has primarily focused on elements of music such as genre (Babić et al., 2021), volume (Farrell, 2021), and tempo (Brodsky, 2001), showing that drivers listening to high volume, fast tempo, and aggressive music have been observed to exhibit more risky behaviours. Perhaps closest to our work is Kari et al. (2021), who designed a "Soundride" interaction system that synchronized music with driving route events. Their findings suggest that these music changes, contingent on driving environments, can act as sound affordances, enhancing the driving experience.

3. Method

3.1. Participants

We determined the required sample size via an a priori power analysis using G*Power in version 3.1.9.6. To achieve a power of 0.8 with an alpha level of .05, twenty-one participants should result in an anticipated medium effect size (0.27 (Funder & Ozer, 2019)) in a within-factors repeated-measures ANOVA with four measurements. Therefore, we recruited twenty-four drivers (Female: 11, Male: 13) with an average age of 29.88 years (SD= 3.72). Participants were recruited through a local communication application or university mailing, and respondents were financially compensated with €10. The human research ethics committee of the Delft University of Technology approved the study.

3.2. Apparatus

The experiment was conducted using a driving simulator situated at Delft University of Technology. Scenarios in the driving simulator were designed using SCANeRstudio 2023 software (AVSimulation, 2023) developed by AV Simulation. Illustrated in Figure 1, the driving simulator is a fixed-base setup comprising a dashboard mock-up equipped with three 4K high-resolution screens, offering approximately 180° field of vision. It incorporates a Fanatec steering wheel and pedals. We used a portable eye-tracker, Pupil Invisible, an eye-tracking platform developed by Pupil Labs, to collect participants' eye movement data.

Figure 1. Driving simulator.

Table 1. UI conditions.

	1. Baseline	2. Music dimming	3. Road noise amplifying	4. Music dimming and road noise amplifying
Visual (−30s)	Countdown of the remaining time (time budget)			
Soundscape (−30s ∼ −10s: Pre-alert phase)	No sound change	Dimming music	Amplifying road noise	Dimming music + Amplifying road noise
Take-over request (−10s)	Beeps			

3.3. Experiment design

The simulator experiment had a within-subjects design, so each participant experienced four user interface (UI) conditions, as shown in Table 1: (1) *Baseline*, (2) *Music dimming*, (3) *Road noise amplifying*, and (4) *Music dimming and road noise amplifying*. During driving, music was played in the background in all UI conditions, and the driving mode was presented on the visual display. In addition, in all UI conditions, from 30 s before the system limit, the remaining time is displayed in the upper left corner of the front display, and from 10 s before the system limit, the take-over request is provided through an auditory beep. The difference between UI conditions is how the background sound (music and road noise) changed from 30 s to 10 s before the system limit. In the *Baseline*, the background sound did not change. In the *Music dimming*, the music gradually dimmed. In the *Road noise amplifying*, road noise gradually amplified. In the *Music dimming and road noise amplifying*, the music gradually dimmed while road noise amplified. All sounds used in the experiment are provided in the Supplementary Materials.

3.4. Scenario

The experiment involved highway driving scenarios in foggy weather, encompassing three different take-over situations from automated driving to manual control. Participants operated automated vehicles and engaged in a visual-motor 2-back task using a tablet as a secondary task during automated driving. The scenario assumed that only non-urgent, scheduled take-overs occur. This scenario can correspond to SAE Level 3 or SAE Level 4, where in Level 3, drivers' action would be required to ensure safety, while Level 4 automation would ensure safety if drivers failed to act timely. We did not specify a particular driving automation level or safety implications to the participants. Still, we mentioned that participants could see the remaining time before take-over in all user interface conditions. Heavy fog conditions prompted the three takeovers, signalling drivers to assume control. The scenario's timeline is illustrated in Figure 2. The scenario began with the participant driving in automated driving mode at 90 km/h in the right lane of a two-lane highway. After 120 s, the vehicle anticipated entering a foggy section, presenting a soundscape to the drivers with a 30-second time budget. A soundscape was

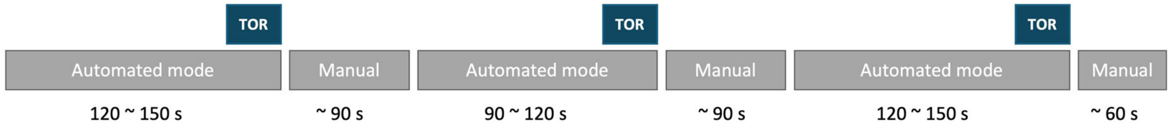

Figure 2. Scenario timeline.

Figure 3. The current driving mode is shown in the upper right corner (red box), and the countdown time is shown in the upper left corner (yellow box).

presented between 30 and10 s before the limit, depending on each condition. The take-over request was presented 10 s before the system limit. The drivers had the option to assume control using a button on the steering wheel after the take-over request was presented. After taking control, the drivers drove manually. After passing the foggy road, the car provided a hand-over indication ("Automated driving is available, please press the button"). When drivers pressed the button on the steering wheel, automated driving started, and they resumed the secondary task. This take-over situation was repeated twice more before finishing the scenario.

3.5. User interface design

Visual information, including current driving mode and countdown time, was provided on the front main display, as shown in Figure 3, and sounds were delivered through the built-in simulator speakers. Across all interface conditions, the current driving mode (automated or manual mode) was consistently displayed in the upper right corner of the front main display. In addition to the visual mode indication, an auditory cue was provided whenever the drivers switched between automated and manual modes. A countdown time (from 30s to 0s) was provided in the upper left corner of the front main display.

Additionally, when a car passed the foggy conditions, and the automated mode was available, a pre-recorded text-based female voice sound was presented: "Automated driving available; please press the button." A take-over request, in the form of a beep, was presented 10s before the system limit under all UI conditions. When the take-over request was initiated, background music and road noise were muted, and the take-over request was delivered at 65 dB. It lasted for 10 s and consisted of 10 repetitions of a 1-second tone composed of a 649 Hz and a 2439 Hz frequency. The beep (Kim et al., 2022) was designed specifically for automated vehicles using Logic Pro X, employing wood and xylophone sound elements.

Road noise and music were continuously presented during automated and manual modes, excluding the final take-over request period. The road noise, recorded by the SCANNER driving simulation, predominantly a 93.5 Hz tone, was simulated based on findings by Ma et al. (2017) indicating that electric vehicles travelling at 90–100 km/h produce a noise level of 45–50 dB. The music tracks used in the study were based on the track "The Beat of Nature" by Kaplunskyi (2022), loosely categorized as

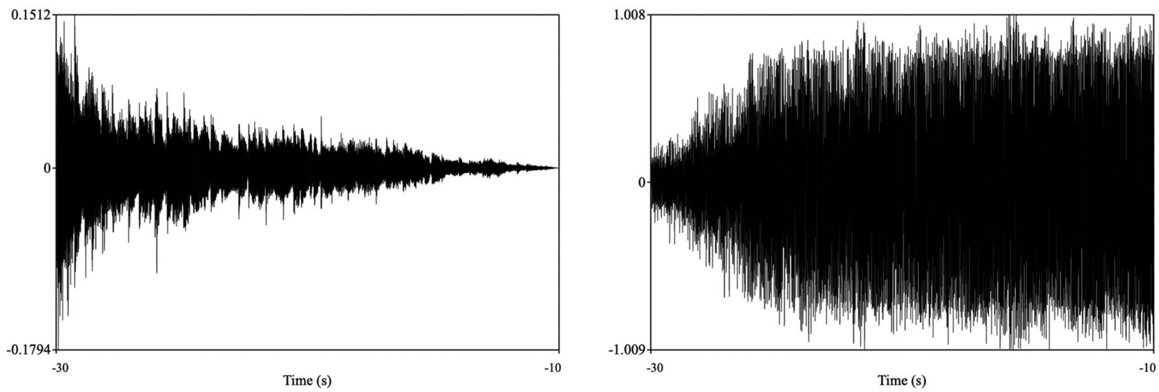

Figure 4. Intensity (relative amplitude) changes of music during music dimming (left) and road noise during road noise amplifying (right).

"Acoustic, Acoustic Guitar." This music is royalty-free and can be used freely based on the Pixabay content license. The track tempo was 108 bpm. This track was chosen primarily because it lacked significant dynamics or key changes that could distract the drivers' attention. In this exploratory stage of the research, we aimed to use ambient music that provided a relatively stable, emotionally neutral background that would not significantly affect driving performance or develop a strong emotional attachment (Burnett et al., 2017). The music consisted of six distinct sections, each lasting between 75 and 150s, and was continuously played during the driving task. The music was presented at 60–65 decibels. This decibel level was selected based on previous studies (Naujoks et al., 2019; Nees & Walker, 2011), which suggest that a sound should be between 15 and 30 dB above the background noise to be detected by drivers, especially in a driving environment.

Figure 4 shows the intensity change of music during *Music dimming* and road noise during *Road noise amplifying* between 30 s and 10 s before the system limit. In *Music dimming*, music intensity gradually decreased from 30 s before the system limit, reaching 10 dB. In the *Road noise amplifying*, road noise intensity gradually increased from 30 s before the system limit, reaching 78 dB. The change in road noise and music was merged in the *Music dimming and road noise amplifying*.

3.5. Secondary task

Participants were asked to perform a 2-back task on the tablet on the desk near the lower part of the centre console. This secondary task is a visual-motor task without sound. The task is visually and cognitively demanding (Kane et al., 2007), self-paced and interruptible, so participants could pause it whenever they want to check the driving environment. In a 3×3 grid of nine boxes, the red position of a box changed randomly every 2s. If the current red position was the same as the red position two steps earlier, the participant could press the button on the screen.

3.6. Measurements

3.6.1. Objective measurements

Take-over reaction time refers to the time drivers take to reengage the vehicle control (Gold et al., 2015). We measured take-over reaction time as the time participants pressed the disengagement button on the steering wheel from the time the soundscape was initially issued, 30 s before the system limit. Takeovers in which participants missed the transition were treated as failures. Eye-movement data were collected to track when participants looked at the road for the first time after the soundscape was issued. In this study, the time from when the soundscape was triggered to when participants first looked at the road is referred to as the "initial glance" time. For the baseline condition without soundscapes, the initial glance was measured as the time from 30 s before the system limit was applied until participants first looked at the road.

3.6.2. Subjective measurements

After each UI condition simulation, participants answered a questionnaire regarding workload, situation awareness, acceptance, and perceived urgency. When a new interface is introduced, drivers may experience an increased workload as they develop an understanding of the information it presents and how to use this information. To determine the effect of different UIs on driver workload, we used the DALI (Driving Activity Load Index) questionnaire (Pauzie, 2008), a modified NASA-TLX (Hart & Staveland, 1988) to adapt to the driving task workload. Participants answered a 7-point Likert questionnaire consisting of six items (effort of attention, visual demand, auditory demand, temporal demand, interference, and situational stress). Additionally, situation awareness was measured using the subscale of the Situation Awareness Rating Technique (SART) (Taylor, 2017) to evaluate whether drivers are aware of driving situations through the UIs. We used the dimension of "understanding the situation" from SART. Participants answered a 7-point Likert questionnaire consisting of three items (information quantity, information quality, and familiarity with the situation). Considering UIs' real-world applicability, it is important to evaluate whether the proposed soundscape system is acceptable to drivers and perceived positively. To evaluate acceptance, participants answered nine items (1. Useful – useless, 2. Pleasant – unpleasant, 3. Bad – good, 4. Nice – annoying, 5. Effective – superfluous, 6. Irritating – likeable, 7. Assisting – worthless, 8. Undesirable – desirable, and 9. Raising alertness – sleep inducing) using a 7-point Likert scale questionnaire (van der Laan et al., 1997). The scores for items 1, 2, 4, 5, 7 and 9 were reversed in the calculation. The sum of items 1, 3, 5, 7, and 9 divided by 5 describes the Usefulness scale, and the sum of items 2, 4, 6, and 8 divided by 4 describes the Satisfying scale. As the number of in-vehicle interfaces increases, it becomes important to ensure that the perceived urgency of signals is mapped and conveyed at the intended level of urgency (Baldwin & Lewis, 2014; Hellier et al., 1993). Drivers responded to a 7-point Likert scale question to indicate their perceived level of urgency. After all simulations, the preference rank (1 – Best, 4 – Worst) on the four types of interfaces was measured.

3.7. Procedure

Participants were first introduced to the experiment. They were required to read the experiment information and sign an informed consent form. They completed a demographic questionnaire about age, gender, driving experience, and visual and auditory acuity. They proceeded to the driving simulator. Individual seating adjustments were made according to their preferences. The experimenter read the following information: "You're driving on a highway in an automated car. The highway is partially foggy. In 'automated mode,' the car drives without input; you don't need to keep your hands on the steering wheel or monitor the road. You will play the tablet games we provide. However, when the car's system detects fog and determines it is too difficult to drive autonomously, it will request a take-over. Then, you will switch to 'manual mode' by pressing the blue button on the steering wheel. You can take over anytime between when you start perceiving the takeover request and the vehicle's driving limit − 0 on the countdown. In 'manual mode,' you control the pedals and steering wheel. Once you pass the foggy situation, the car will inform you that automated driving is available again. You can then switch back to 'automated mode' by pressing the blue button."

Participants drove both automated and manual modes in training sessions to familiarize themselves with the simulator. They experienced take-over situations, changing driving mode using the button, driving manual, and playing a secondary task. Participants were advised they could stop if they felt discomfort or motion sickness. Subsequently, the main simulator experiment started. The main experiment began, including three take-over situations for each UI condition. Take-over reaction time data were collected during the driving task. Each UI condition took approximately 10 min. After each UI condition, participants completed the questionnaire regarding workload, situation awareness, acceptance, and user experience. This process was repeated for the four UI conditions, with the order randomized. After completing the four UI conditions, participants ranked their UI preferences. The entire procedure lasted around one and a half hours.

3.8. Data analysis

Statistical analysis was conducted using IBM SPSS ver.27 and JMP ver. 17. The data were analyzed using a separate repeated-measures analysis for each dependent factor (eye-gaze behaviour, take-over reaction time, situation awareness, workload, acceptance, and user experience) with UI as an independent factor (four levels). The effects were declared statistically significant if $\alpha < 0.05$. Before ANOVA analysis, we checked sphericity. If Mauchly's Test of Sphericity is statistically significant ($p < 0.05$), meaning that the hypothesis of the variances of the differences is equal was rejected, Greenhouse-Geisser adjustment was reported. We use Tukey HSD for *Post-hoc* analysis ($p < 0.05$).

4. Results

4.1. Reaction time

The reaction time has been analyzed in each of the conditions. There was no failed take-over case. As shown in Figure 5, there was a significant difference in reaction time ($F(3, 69) = 4.53$, $p = 0.006$, $\eta^2 = 0.17$). *Post-hoc* analysis indicated that the reaction time in the *Music dimming and road noise amplifying* was significantly faster than in the *Baseline.*

4.2. Initial glance time

In the data collection process, we found that the eye-tracking data of six participants were improper for data analysis. So, we analyzed eye-tracking data using eighteen participants' data. As shown in Figure 6, there was a significant difference in the initial glance time ($F(3, 42) = 4.66$, $p = 0.007$, $\eta^2 = 0.25$). *Post-hoc* analysis indicated that the initial glance time of the *Music dimming and road noise amplifying* was significantly faster than the *Baseline*.

4.3. Workload

There was a significant difference in Visual demand ($F(3, 69) = 2.83$, $p = 0.045$, $\eta^2 = 0.11$). *Post-hoc* analysis indicated that the Visual demand in *Music dimming and road noise amplifying* was significantly lower than the *Baseline,* as shown in Figure 7. However, there were no significant differences in the

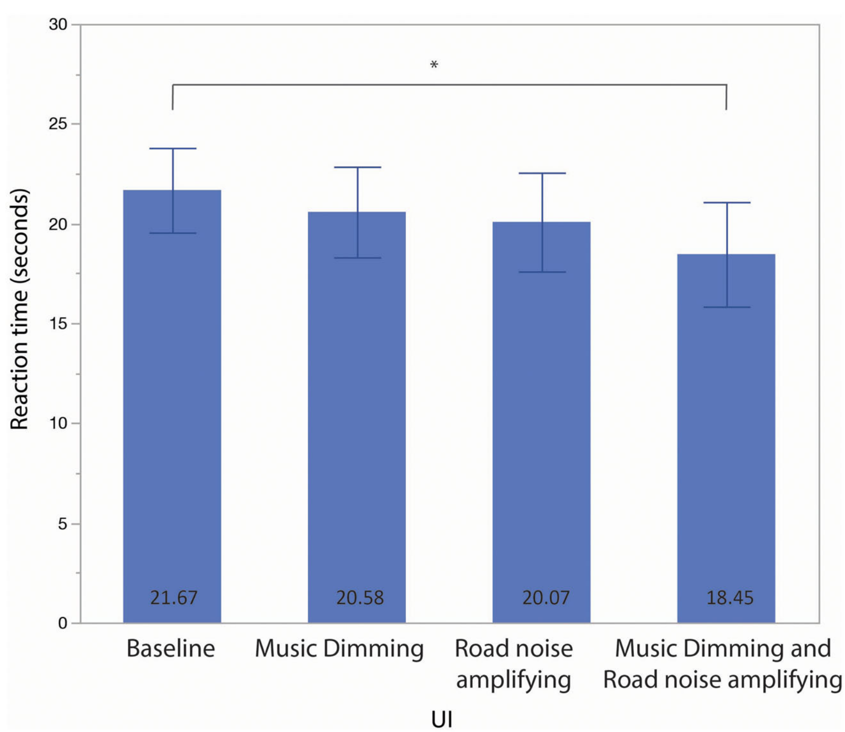

Figure 5. Mean of reaction time for UI conditions (error bars reflect within-subject standard error of the mean).

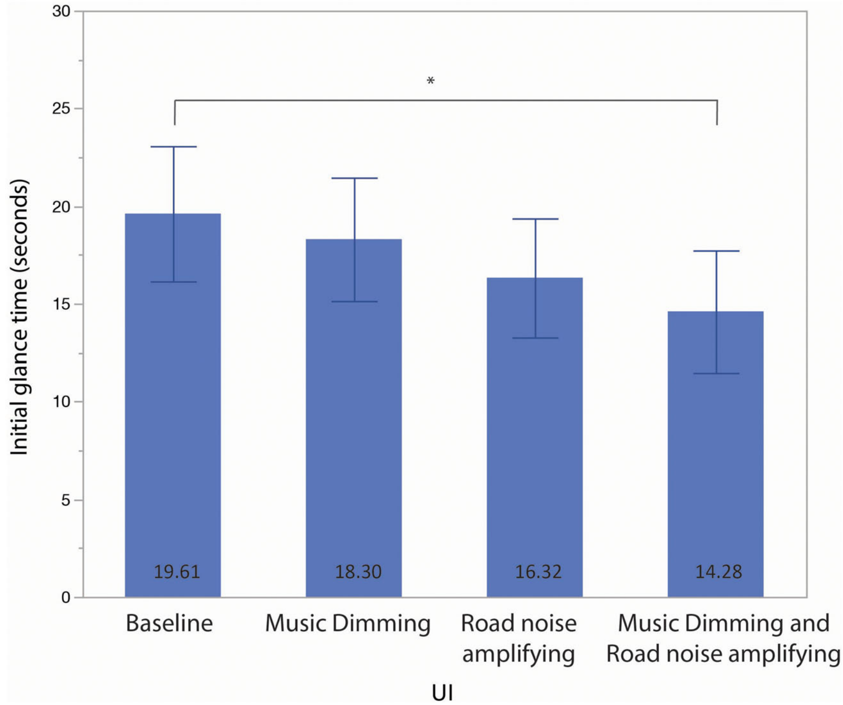

Figure 6. Mean of the initial glance time for UI conditions.

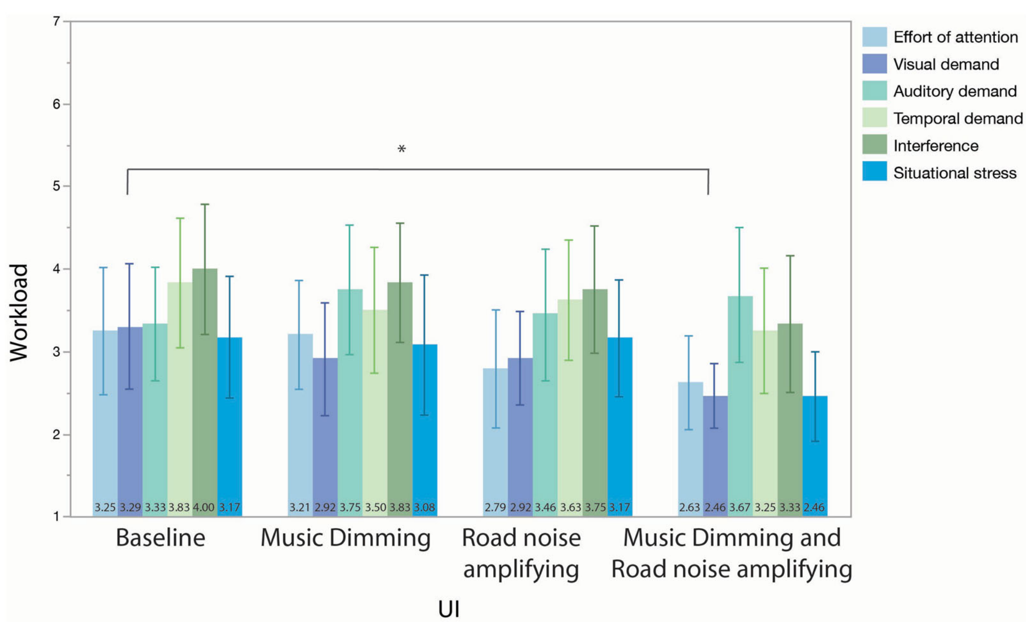

Figure 7. Mean of workload for UI conditions.

other workload scales Effort of Attention ($F(2.38, 54.83) = 1.44$, $p = 0.238$, $\eta^2 = 0.06$) with a Greenhouse-Geisser adjustment between UI conditions, Auditory demand ($F(3, 69) = 0.72$, $p = 0.544$, $\eta^2 = 0.03$), Temporal demand ($F(3, 69) = 1.12$, $p = 0.391$, $\eta^2 = 0.04$), Situational Stress ($F(3, 69) = 1.54$, $p = .212$, $\eta^2 = .06$), and Interference ($F(2.13, 49.02) = 1.43$, $p = 0.249$, $\eta^2 = 0.06$) with a Greenhouse-Geisser adjustment between UI conditions.

4.4. Situation awareness

There was a significant difference between UI conditions in Quantity ($F(2.13, 48.93) = 6.29$, $p = 0.003$, $\eta^2 = 0.21$) with a Greenhouse-Geisser adjustment, and Quality ($F(3, 69) = 2.75$, $p = 0.049$, $\eta^2 = 0.11$),

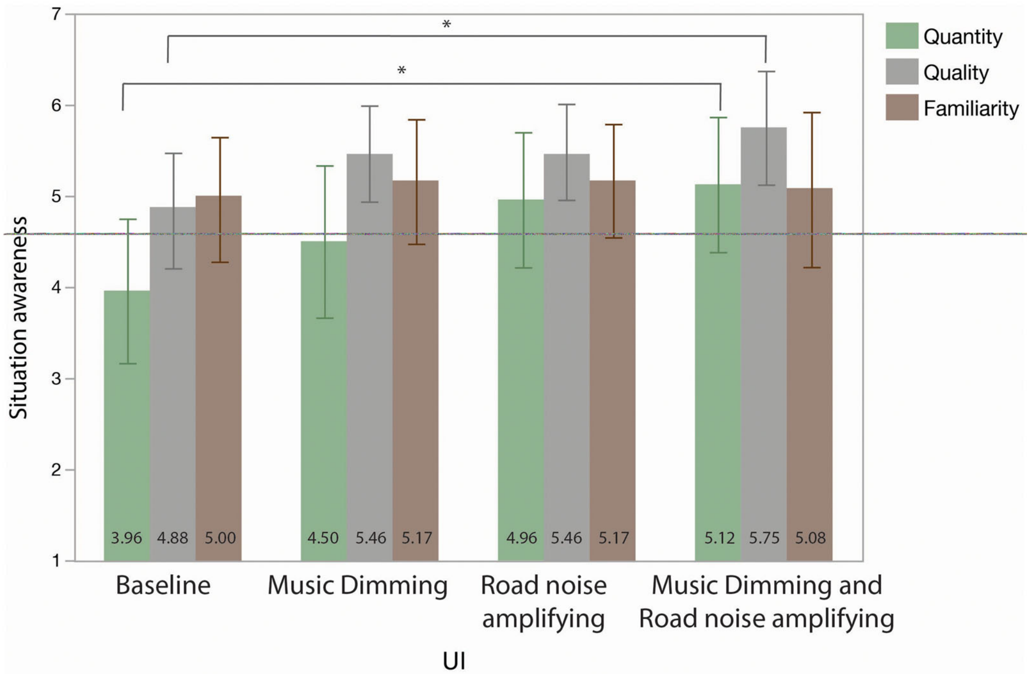

Figure 8. Mean of situation awareness for UI conditions.

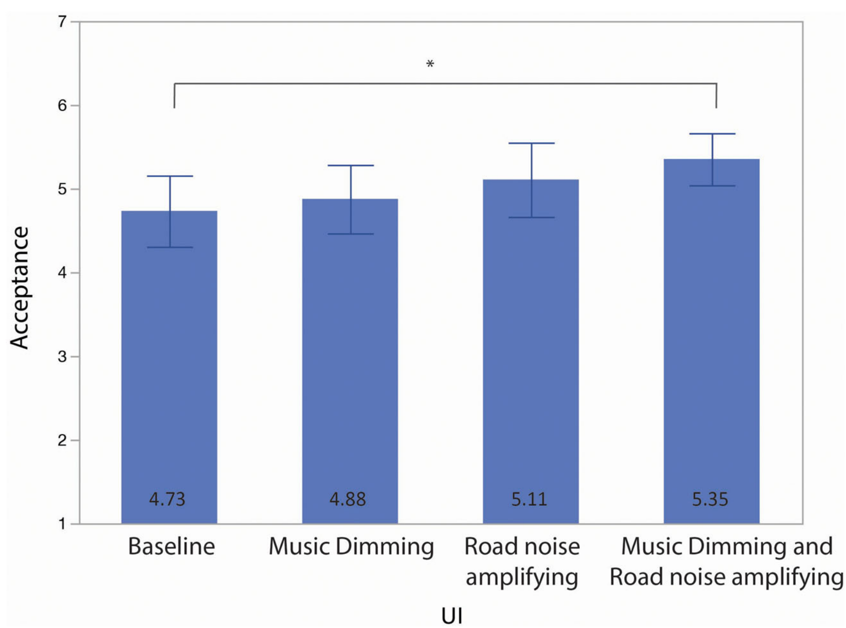

Figure 9. Mean of acceptance for UI conditions.

as shown in Figure 8. *Post-hoc* analysis showed that *Music dimming and road noise amplifying* was significantly higher than the *Baseline* in Quantity and Quality, and the *Road noise amplifying* was significantly higher than *Baseline* in Quantity. There was no difference in Familiarity ($F(2.27, 52.10) = 0.20$, $p = 0.896$, $\eta^2 = 0.01$) with a Greenhouse-Geisser adjustment.

4.5. Acceptance

The reliability (i.e., Cronbach's α values) of Acceptance items was 0.806, which exceeded the recommended value ($\alpha = 0.7$) (Carmines, 1979). As shown in Figure 9, the *Baseline* received the lowest acceptance, and the *Music dimming and road noise amplifying* received the highest acceptance. There

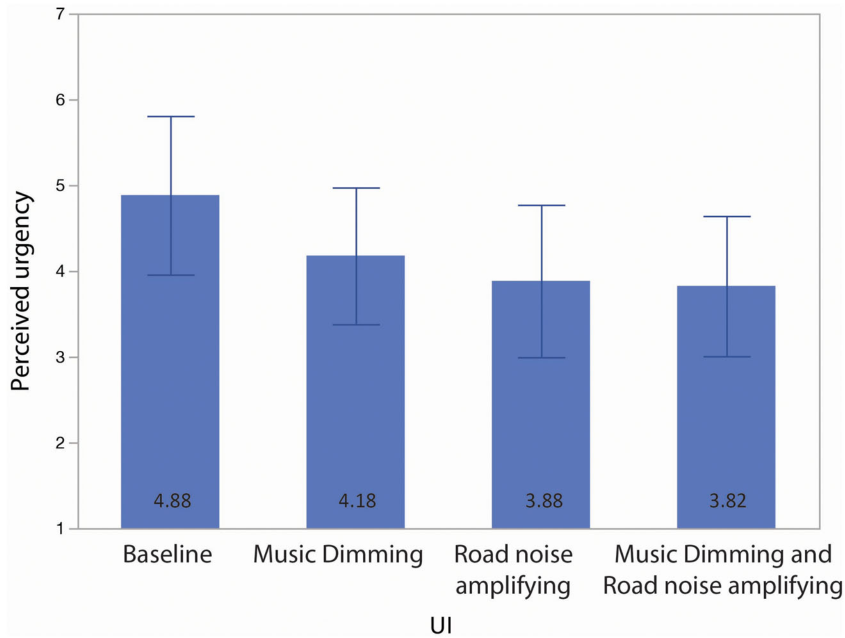

Figure 10. Mean of perceived urgency for UI conditions.

was a significant difference between UI conditions ($F(3, 69) = 5.11$, $p < 0.05$, $\eta^2 = 0.18$). *Post-hoc* analysis showed that the *Music dimming and road noise amplifying* was significantly more accepted than the *Baseline*.

4.6. Perceived urgency

There was no significant difference in Perceived urgency ($F(2.13, 48.88) = 2.30$, $p = 0.108$, $\eta^2 = 0.09$) with a Greenhouse-Geisser adjustment between UI conditions, as shown in Figure 10.

4.7. Preference ranking

Concerning the ranking of the UI preference, the Friedman test showed that participants ranked the four UI conditions significantly differently ($\chi^2(3,27) = 15.76$, $p < 0.001$). *Post-hoc* comparisons indicated that participants rated *Baseline* significantly lower as compared to *Music dimming and road noise amplifying*.

5. Discussion

In this study, we presented a soundscape study with twenty-four participants in a scheduled non-urgent take-over situation to investigate the effects of road noise and background music soundscapes on transition safety and user experience. We found that soundscapes are natural signals for communicating take-over situations in automated vehicles. Additionally, they significantly enhance take-over safety and user experience. In this discussion, we will evaluate the findings in the context of existing research, considering the implications for user experience, safety, and design.

5.1. Impact of soundscapes on safe take-over

The results show that both soundscapes, particularly combining *Music dimming and road noise amplifying*, significantly enhance drivers' ability to take over control from an automated vehicle. The faster reaction times with *Music dimming and road noise amplifying* indicate that these soundscapes effectively capture drivers' attention and prepare them for the take-over. The significant differences in both reaction time and the initial glance time highlight the role of auditory alerts in enhancing situation awareness and promptness, which aligns with previous studies (Beattie et al., 2014; Petermeijer et al., 2017; van der Heiden et al., 2017). In this study, a 20-second time budget was given for the pre-alert phase. In the *Music dimming and road noise amplifying* condition, drivers looked at the driving environment approximately 5 s earlier than in the *Baseline* (*Baseline*: 19.61 s, *Music dimming and road noise amplifying*: 14.28 s) and initiated the take-over 3 s sooner (*Baseline*: 21.67 s, *Music dimming and road noise amplifying*: 18.45 s). There may be questions about whether these time improvements are practically meaningful. In scenarios where there is ample time for a safe take-over, a reduction of a few seconds might seem insignificant. However, in the *Baseline*, drivers only began to visually check the driving environment around the time of the final take-over request (beep), which was issued 20 s after the soundscape was issued, and they performed the take-over shortly thereafter. In contrast, with *Music dimming and road noise amplifying,* drivers assessed the road situation before the final take-over request and completed the take-over before it was even issued. Additionally, the time difference between the initial glance at the road and the take-over was 2 s in the *Baseline*, compared to roughly 4 s with *Music dimming and road noise amplifying*. This indicates that with *Music dimming and road noise amplifying,* drivers had more time to assess the situation, increasing the likelihood of a more informed response. The final take-over request, which uses high urgency beeps, prompts a quick response, but a rapid reaction does not necessarily ensure that the driver fully understands the situation. For this reason, although the time differences might appear small, the *Music dimming and road noise amplifying* shows evidence of supporting a higher level of driver awareness and responsiveness, contributing to overall system safety. Moreover, the significant improvements in both the quantity and quality of situation awareness suggest that these auditory cues help drivers respond more quickly and enhance their overall understanding of the driving environment. This is particularly important in automated driving, where the driver's role may shift from passive monitoring to active control in a short period. The enhanced situation awareness observed in this study indicates that drivers are better equipped to understand and react to their surroundings when these soundscapes are used, potentially reducing the likelihood of errors during takeovers. This aligns with previous research (Ho & Spence, 2005) suggesting that auditory cues can be powerful tools for alerting drivers without being overly intrusive.

The soundscapes tested provided a significant difference in workload only for visual demand. In line with van der Heiden et al. (2017), as in the baseline drivers cannot rely on an auditory signal to warn them; they use visual attention to check the driving situations and the visual countdown display. Therefore, the *Baseline* was in high visual demand compared to other conditions, significantly higher than the *Music dimming and road noise amplifying*. The soundscapes subtly modify the driver's environment without introducing entirely new stimuli, and this approach does not increase workload by integrating the takeover alert into the existing soundscape.

5.2. Impact of soundscapes on user experience

Previous studies have shown that auditory signals are highly effective but can also induce annoyance. The high acceptance scores and preference rankings for our combined soundscape *Music dimming and road noise amplifying* demonstrate that a take-over request that integrates seamlessly with the existing auditory environment is perceived positively by users while still effectively conveying information. This tendency to prefer quiet, naturalistic cues may result from the idea of "flow" in human-computer interaction—users want experiences that allow them to find and maintain rhythm within a task without many disruptions (Csikszentmihalyi et al., 2005). In this context, soundscapes that subtly cue the driver without breaking their concentration might be perceived as more user-friendly and less stressful, contributing to higher acceptance. However, not all participants were aware of the changes in the soundscape, and some even found the auditory modifications slightly annoying. This highlights a potential challenge in designing soundscapes that are both effective and universally appealing. While most drivers might appreciate the subtlety of these cues, some drivers might miss these signals, particularly if they are focused on other tasks or if the changes are too subtle. Therefore, designers need to carefully balance subtlety with perceptibility to ensure that cues are both effective and broadly accepted.

The *Music dimming and road noise amplifying* effectively enhanced reaction times and was preferred by users.

The urgency reduced insignificantly ($p = 0.09$), which could be seen as both a benefit and a limitation. On the one hand, the lack of perceived urgency might indicate that these soundscapes are more suitable for a non-emergency take-over situation, where the goal is to smoothly transition control back to the driver without causing unnecessary alarm. This is particularly relevant when drivers have sufficient time to take over, and the transition can be managed calmly without inducing stress. On the other hand, in scenarios where immediate action is required, the subtlety of these cues might be a disadvantage.

5.3. Implications for design

The use of natural soundscapes, such as *Music dimming and road noise amplifying*, offers a promising approach to enhance both safety and user experience during takeover events. However, one of the key challenges highlighted in this study is ensuring that the soundscape is perceptible to all users and considering the context in which it is presented. While our scenarios demonstrated effectiveness as a non-emergency take-over request, critical situations requiring immediate response may necessitate supplementing these cues with more explicit warnings, such as a high-urgency auditory alert or haptic feedback, to ensure full awareness of the situation. Furthermore, although we employed natural signals derived from driving contexts, the efficacy of introducing novel sounds, which are unrelated to driving, to reduce the ambiguity of the meaning of sound can be explored. Sounds from nature, such as bird songs, can be an example which positively affects the restoration of attention (Zhang et al., 2017).

5.4. Limitations and future work

While this study demonstrated the effectiveness and acceptance of soundscapes, several limitations warrant further study. Our study involved a moderate number of participants ($N = 24$) who were relatively young (on average, 29.88 years old) in scheduled TOR, calling for the exploration of diverse demographics, driving conditions, and levels of driving automation. For example, older drivers may respond differently than younger drivers and varying driving environments may necessitate augmented auditory cues. In addition, this study assessed situation awareness using subjective measurements, which reflect the driver's self-reported perception of their situational understanding. However, these subjective indicators may not perfectly capture whether drivers were truly aware of the situation. The importance of situation awareness lies not only in executing the take-over within the allotted time but also in supporting safe manual driving after the take-over. To accurately determine the user interface's impact on safe driving, it is recommended that situation awareness and driving performance after TOR be examined in further studies. Furthermore, this simulator study, which had relatively short driving durations, focused on the feasibility of soundscape, drivers' reactions, and preferences. Future studies should investigate how soundscapes influence driver behaviour and safety over time, preferably in naturalistic on-road conditions, including the potential for auditory habituation (Fruhstorfer et al., 1970). In this study, we tested music dimming and road noise amplification as part of using natural signals related to the driving situation. Further research could explore the design of alternative soundscapes, such as nature or futuristic sounds, that can alter the atmosphere or indicate situational changes. In addition, further study could use reading or listening as a secondary task, which is more natural in the driving context, and evaluate the impact of soundscapes on secondary task performance and their interaction. While there are limitations to the effectiveness of human factors research conducted under constrained conditions (de Winter et al., 2021), this study nonetheless demonstrates the potential of the soundscape concept in enhancing awareness of upcoming situations.

6. Conclusion

Although various auditory interfaces for take-over requests have been explored, limited attention has been given to ambient, non-intrusive soundscapes that use existing driving-related sounds. This study evaluates whether soundscapes can enhance safety and user experience during take-over situations in automated vehicles. We designed soundscapes using sounds that drivers are naturally exposed to in vehicles, such as music and road noise. The experiment was conducted in a driving simulator during scheduled take-over situations, which are not urgent situations. The results indicate that soundscapes improved reaction time, situation awareness, and acceptance without causing annoyance. Specifically, the combination of music dimming and road noise amplification enhanced drivers' perception and responsiveness, contributing to overall system safety. These findings suggest that natural auditory signals can reduce visual workload, improve situation awareness, and elicit positive responses from drivers.

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