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How manoeuvre information via auditory (spatial and beep) and visual UI can enhance trust and acceptance in automated driving

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ABSTRACT

In conditionally automated driving (SAE level 3), drivers may take their eyes off the road but will still need to be ready to take control and will, therefore, benefit from information on automation. This study aims to investigate the effectiveness of automation manoeuvre information provided through spatial sound, traditional notification sound (beep), and a visual interface. Spatial sounds were designed differentiating four distinct driving manoeuvres: overtaking a leading car, slowing down, turning right, and passing a roundabout. The notification sound consisted of one beep being identical for all manoeuvres. The visual interface showed the automation mode with an image and manoeuvre information with text and images. The impact of these interfaces on trust, workload, acceptance, situation awareness, and sense of control was evaluated with questionnaires and visual attention was evaluated with eye tracking while participants engaged in a visual-motor secondary task in a driving simulator. The results indicate that, with all interfaces tested, manoeuvre information enhances trust, acceptance, situation awareness, and sense of control, without significantly affecting the overall workload. These benefits were more profound, adding auditory information and differed marginally between the traditional notification and the spatial sound, as the effectiveness of the different auditory interface types varied depending on the specific manoeuvre. Findings highlight the importance of designing user interfaces for automation manoeuvre information using auditory cues to improve the user experience in automated driving.

1. Introduction

Automated vehicles are one of the technologies to signal an evolution toward a behaviour change in society (Othman, 2021; Taiebat et al., 2018). Automation in vehicles is expected to be beneficial to safety and comfort and to change the way people use cars (Milakis et al., 2017), such as relaxing or watching while driving. A successful adaptation of technology requires a sense of trust in the collaboration between humans and automated systems. To this end, transparency is crucial to evoking trust in humans (Lyons et al., 2016). Transparency is defined as the understandability and predictability of systems (Endsley et al., 2003). Transparency allows users to understand what the system is doing, why, and what it will be doing next (Alonso & de la Puente, 2018). Lack of transparency in automated vehicles (e.g., Automated vehicle does not inform how they will react in the upcoming situation) will lead to inherent distrust (Basantis et al., 2021). User interfaces (UIs) are used to display information that can improve transparency, such as sensor

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performance, system state and the abilities of automated vehicles. In this study, we have designed user interfaces to enhance transparency and evaluate the effect of the user interfaces on trust and acceptance in conditionally automated vehicles.

1.1. *Information needs in conditionally automated vehicles*

As the performance of automated vehicles (AV) advances, the need for drivers to monitor will reduce. In SAE Level 3 automated vehicles (conditionally automated vehicles), the vehicle can perform driving actions conditionally and requires drivers to serve as fallback-ready users (SAE International, 2021). Automotive manufacturers emphasise the ability of automated vehicles to reduce the cognitive load of driving, allowing users to engage in secondary tasks such as handling a smartphone and watching videos (Cunningham et al., 2019). Nevertheless, it is shown that drivers still want to receive information concerning the actions of their vehicles (Beggiato et al., 2015; Feierle et al., 2020). In addition, this information will enhance trust (Ekman et al., 2018). Furthermore, a driver with a certain level of situation awareness will regain control of a vehicle faster (Lyons, 2013). Moreover, to keep the driver in the loop, continuous feedback improves the driver's ability to know the vehicle's state and detect anomalies (Norman, 1990). Even in conditionally automated driving, it is deemed beneficial to provide automation information (driving situation detected by the system and decisions made by the automated vehicle) to drivers to increase transparency (Carsten & Martens, 2019; Endsley, 2015). Transparency should be designed based on the level of vehicle autonomy and human states, such as acceptance, situation awareness, and workload (Lakhmani, 2019). During conditionally automated driving, it is not mandatory for drivers to monitor all driving situations. Therefore, drivers may only need limited but highly abstracted information. Very detailed information could increase the driver's workload, cause annoyance, and sometimes be unnecessary. Auditory warnings are often designed such that they evoke a sense of high urgency (Politis et al., 2015) or unpleasantness (Özcan & Egmond, 2012). However, the purpose of automation information during automated driving is different from that of warnings. Even though drivers receive information from the vehicle, they do not need to react. The interaction in conditionally automated driving needs to satisfy the demanding conditions that make the driver aware of the situation without causing annoyance. Therefore, driving scenarios and user experience should be considered in the design, especially what information is required and which modality to use to display this information.

1.2. *Automation information to enhance transparency in automated vehicles*

During conditionally automated driving, the system operates the vehicle instead of the driver, and user interfaces can communicate vehicle action. Previous studies have shown that automation information providing vehicle action increases trust and acceptance (Basantis et al., 2021; Ma et al., 2021; Oliveira et al., 2020; Sawitzky et al., 2019; Yucheng Yang, 2017). Oliveira et al. (2020) and Sawitzky et al. (2019) have shown that augmented reality displays can increase trust by providing different visual aids for displaying driving routes. Basantis et al. (2021) found that participants expressed feelings of comfort, trust, and safety when presented with auditory manoeuvre notifications by comparing four distinct interfaces designed to communicate automation actions to rear-seat passengers, which included 1) no feedback, 2) a visual display of the vehicle's path, 3) auditory notifications of vehicle manoeuvres, and 4) a combination of auditory notification and display of the vehicle's path. However, the auditory interface exhibited limitations in directing participants' attention to environmental details. Ma et al. (2021) also found significant effects of visual vehicle action information on drivers' levels of trust in a driving simulator. These studies found requirements of system transparency for automated vehicles. However, there is a lack of studies reporting the impact of different user interfaces on understanding automated driving. Although a few studies (Basantis et al., 2021; Oliveira et al., 2020; Sawitzky et al., 2019) have compared the effects of different interfaces, they did not fully consider the automated driving experience, in which drivers' visual attention is often required for secondary tasks (Cunningham et al., 2019). Hence, the requirements for user interface design for system transparency are not yet very clear. Therefore, in this study, we compared specifically designed interfaces to understand the benefits of system transparency in fostering trust and acceptance and to compare different interfaces presenting manoeuvre information as automation information.

1.3. *Effect of auditory UIs in vehicles*

Visual and auditory interfaces serve as the primary modalities used in vehicles. An auditory interface offers the advantage of capturing attention from all directions (Siwiak & Jame, 2009), regardless of where the driver's visual focus is directed (Liu, 2001). Visual interfaces have the advantage of presenting more information than auditory interfaces in a limited time; auditory interfaces are advantageous for users to provide a somewhat faster response than a visual interface in automated vehicles (Petermeijer et al., 2017; Politis et al., 2015). However, the potential for annoyance among users remains a significant concern in the design of auditory displays (Edworthy, 1998). In addition, sound can draw attention, but there is a limit to providing explanatory information only with sound. While speech can convey narrative information, its use can quickly lead to driver annoyance in automated vehicles (Forster et al., 2017). Furthermore, speech messages are generally longer than abstract sounds, resulting in longer response times. Spatial sounds, characterised by their directionality and movement, offer an intuitive audio expression that can effectively convey automated driving manoeuvres to drivers. These sounds can provide a driving context within the auditory interface. Previous studies (Beattie et al., 2014; Gang et al., 2018; Wang et al., 2017) have found that spatial sound affects drivers in the way of behaviour, situation awareness, sense of control and workload. Beattie et al. (2014) found that spatial cues related to driving actions in both manual and automated driving, such as braking, acceleration, indicator signals, and gear shifts, improved situation awareness and fostered sense of control. Furthermore, the inclusion of additional traffic information through spatial sound has been shown to enhance situation awareness in both manual (Wang et al., 2017) and automated driving (Gang et al., 2018) and reduce the auditory demands (Ho & Spence, 2005) in manual driving. The effect of information delivery may appear differently depending on the modality type, and multimodal is not always effective in automated vehicles (Kim et al., 2021). In this study, we aim to evaluate the impact of visual and auditory interfaces, including spatial sounds, on delivering manoeuvre information to drivers in conditionally automated vehicles.

1.4. Aim of the current study

This study investigates how manoeuvre information affects drivers during conditionally automated driving. We designed and evaluated four user interfaces to provide detected driving situations and manoeuvre of driving automation as manoeuvre information. This study was conducted to find the answer to the following research questions.

1. How do user interfaces of manoeuvre information affect trust and acceptance in conditionally automated vehicles?
2. Does providing detailed auditory information via spatial sounds improve understanding of the vehicle action during automated driving?

As automation advances, it becomes important not only to provide information to enhance trust and acceptance of automated vehicles but also to consider automated driving situations. In this study, we addressed gaps in existing research, the oversight of user experience in conditionally automated vehicles. Specifically, we conducted a consolidated sound design process, including validation, to provide manoeuvre information via spatial and simple sound without annoyance. The study contributes to addressing a sound design approach to provide information taking account of the context of automated driving and provides insights into the impact of different levels of transparency and modalities on trust and user experience. In the following sections, we will detail our research methodology, including UI and experiment design, present the results of the simulator experiment, and discuss their implications for the design of UIs in conditionally automated vehicles.

2. Method

We designed four user interfaces (UIs) providing automation manoeuvre information via visual-only, visual plus notification sound, visual plus spatial sound, and no manoeuvre information as a baseline. The UIs were evaluated by measuring eye-gaze behaviour, situation awareness, trust, sense of control, workload, and acceptance in a driving simulator.

2.1. Participants

Twenty-seven drivers volunteered in the experiment. Twelve were female, and fifteen were male. The average age of participants was 31 years (SD = 8.58, Min = 24 and Max = 59). All had a valid driving license for more than one year and had no problem with visual and auditory acuity. Participation was recruited through a local communication application or university mailing, and the respondents were financially compensated with €15. The study was approved by the Human Research Ethics Committee of the TU Delft.

2.2. Apparatus

Participants experienced UIs in scenarios in the DAVSi driving simulator with a Toyota Yaris cockpit (Fig. 1) at Delft University of Technology. It used three high-quality projectors to display the environment on the cylindrical 180-degree screen. The visual UI consisted of a 10.1-inch tablet on the centre console. Auditory information was presented using a 5.1 channel speaker system, which was strategically placed on the front of the centre console, as well as on the left and right front, left and right rear under the door trim of the vehicle. A woofer, located under the passenger seat, was used to amplify the sounds. To collect eye-gaze behaviour data, we used a fixed four-camera called Smart-Eye, which tracks the participant's pupil to determine the region of interest. The cameras were placed

Fig. 1. Exterior and Interior of the DAVSi simulator.

on the left and front side of the upper cockpit, right downside of the centre console, and rear mirror, and data was extracted using MATLAB R2022.

2.3. Experimental design

The simulator experiment had a within-subjects design, so one participant experienced four UI conditions in random order as shown in Table 1: 1) *Baseline*, 2) *Visual-only*, 3) *Notification*, and 4) *Spatial sound*. The *baseline* only included the automation mode symbol in the visual display. In the *visual-only*, in addition to automation mode, manoeuvre information was provided using a visual interface without sound. The *Notification* and the *Spatial sound* condition present manoeuvre information through visual and auditory modalities. In the *Notification*, an abstract sound (beep) was provided. In the *Spatial sound*, the sound position in the interior dynamically reflected the vehicle manoeuvre and the position of other road users.

2.4. Scenario

The experiment consisted of highway driving scenarios, each featuring four different manoeuvres. While driving, participants drove conditionally automated vehicles and were asked to engage in a tablet typing task as a secondary task. The four manoeuvres - *'Overtake', 'Turn right', 'Slow down'*, and *'Roundabout'* - were selected by the H2020 HADRIAN project (Stojmenova & Sodnik, 2019). Throughout these manoeuvres, no automation failures or take-over requests were designed, and hence drivers were not expected to take any action. The timeline of the scenario is illustrated in Fig. 2. The scenario began with the participant driving at a speed of 90 km/h in the right lane of a two-lane highway. During the first manoeuvre, the speed of the preceding vehicle was slow, so the participant's vehicle moved to the left lane and overtook the preceding vehicle before returning to the first lane. The vehicle continued driving on a straight road until it encountered a traffic jam, causing the speed to decrease with a $-5\ \mathrm{m/s^2}$ acceleration. After the traffic jam cleared, the vehicle sped up and continued driving on the straight road. The next manoeuvre involved changing lanes to the exit lane of the highway, followed by a change in the road to a one-lane road. Finally, the vehicle passed through a 20-meter-diameter roundabout and exited the opposite road. The vehicle continued driving on a straight road until it stopped.

2.5. UI design

2.5.1. Visual UI

The visual interface always showed the automation mode even in the baseline (Fig. 3) with a driving symbol designed in the H2020 HADRIAN project (Trösterer et al., 2021). The visual-only interface added visual manoeuvre information with five states presented with text and images (Table 2).

2.5.2. Auditory UI

Auditory UIs were played through the surround Dolby 5.1 speakers slightly before vehicles began a manoeuvre. The manoeuvres did not represent emergency situations, and drivers were not expected to react. Hence, sounds were designed to be informative rather than urgent. Sounds were created in Logic Pro X, a digital audio designing and editing software. Its Sculpture's physical model (Fig. 4 left) was used for sound design as a basis. It enables quick exploration of timbres based on materials like nylon, wood, glass, and steel and according to spectral properties in timbre, harmony, and intensity. We used the wood and xylophone style as the main timbre, which is universal in nature and of which it is shown it evokes a sense of simplicity for listeners (Özcan & Egmond, 2012). Using Final-cut Pro version 10.6.4, output speakers were assigned to produce a spatial effect (Fig. 4 right).

2.5.2.1. Notification sound. The beep in the *Notification* condition was designed for automated vehicles and validated in our previous study (Kim et al., 2022). The spectrogram of the sound is displayed in Fig. 5. The duration of the sound is 1 s, and it begins with a 0.05-second sound at a frequency of 989 Hz, followed by a combination of frequencies of 989 Hz and 1478 Hz for the subsequent 0.07 s. After that, the sound consists of a mix of frequencies of 989 Hz, 1478 Hz, and 656 Hz for the remaining 0.84 s.

2.5.2.2. Spatial sounds. Fig. 6 includes a spectrogram of the four spatial sounds that were used to discriminate the four manoeuvres. During the *Overtake* manoeuvre, a 4.5-second sound with a mix of 145 Hz, 192 Hz, and 385 Hz every 1.5 s is played through the front left speaker to indicate that the vehicle is moving into the left lane to overtake the vehicle ahead. As the driver's vehicle passes the leading vehicle on the right lane, 1174 Hz and 1564 Hz are played through the right front speaker and then gradually shifted to the rear speaker. When the overtaking is completed and the vehicle returns to its original lane, a 9-second blend of 145 Hz, 192 Hz, and 385 Hz every 1.5 s is played through the front right speaker. Once the vehicle returns to the main lane, a 3-second sound is played through both

Table 1
Experimental design with information and modality as independent variables.

	1. Baseline	2.Visual-only	3. Notification	4. Spatial sound
Visual	Automation mode icon	Automation mode icon + Manoeuvre information		
Auditory	No sound	No sound	Abstract sound (beep) which is identical for all manoeuvres	Spatial sound which is different for each manoeuvre type

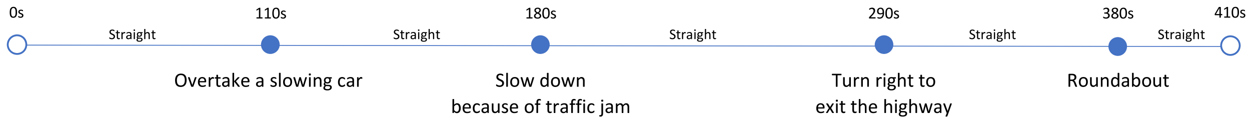
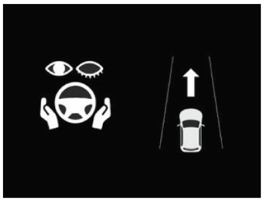
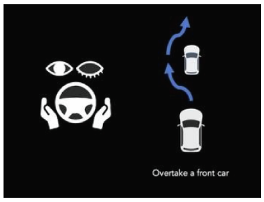
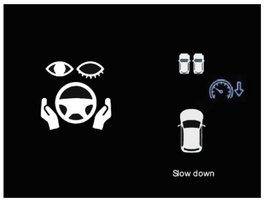
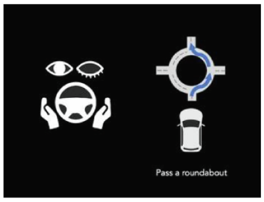


Fig. 2. Scenario timeline.

Fig. 3. Visual UI in *Baseline.*

Table 2
Visual UI - The right parts provide manoeuvre information shown in conditions *Visual-only, Notification,* and *Spatial sound.*

Situation	Normal driving	Manoeuvres	
		Overtake	Slowdown
Visual interface			
		Turn right	Roundabout
			

side speakers. In the slowdown manoeuvre, the sound starts from the front left and right speakers to provide a deceleration feeling, gradually decreasing the volume from the front speakers while increasing it from the back left and right speakers. This sound ranges from 14 Hz to 334 Hz and lasts 3.1 s. In the right turn manoeuvre, the right front speaker plays mixed sounds of 145 Hz, 192 Hz, and 385 Hz for 6 s with a 1.5-second interval. After the vehicle moves to the right lane, the front left and right speakers play a sound for 4.5 s. During the *Roundabout* manoeuvre, a sound mixture of frequencies consisting of 68 Hz, 260 Hz, and 1050 Hz starts from the front left speaker and moves to the front right speaker and back right speaker to indicate that the vehicle is passing through the roundabout. This sound lasts for 13 s while driving through the roundabout. Additionally, a mixed sound of 145 Hz, 192 Hz, and 385 Hz is played through the front right speaker for 6 s with a 1.5-second interval starting from 4 s to indicate that there is a right turn to pass through

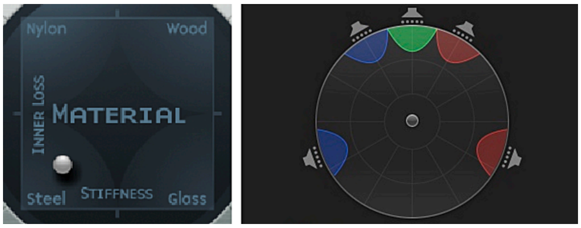


Fig. 4. Left: Logic Pro X, Right: Final-cut Pro.

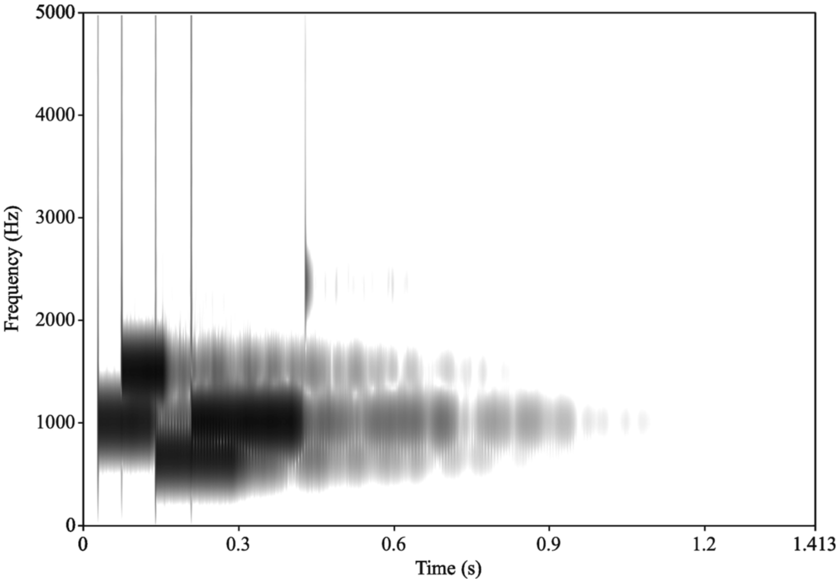


Fig. 5. Spectrogram of the notification beep.

the roundabout. After passing through the intersection, a sound is provided from both the left and right front speakers for 4.5 s.

Sounds were designed over multiple iterations, with indirect feedback from the research group with experts in sound design. After the sound design, sounds were validated to ensure the design intention was aligned with the driver's perception. These sounds can be found in the digital appendix. The beep and spatial sound level was 60–80 dB during the experiment. An in-vehicle embedded speaker presented the underlying sound (road noise), which was 40–50 dB recorded by the SCANNER driving simulation.

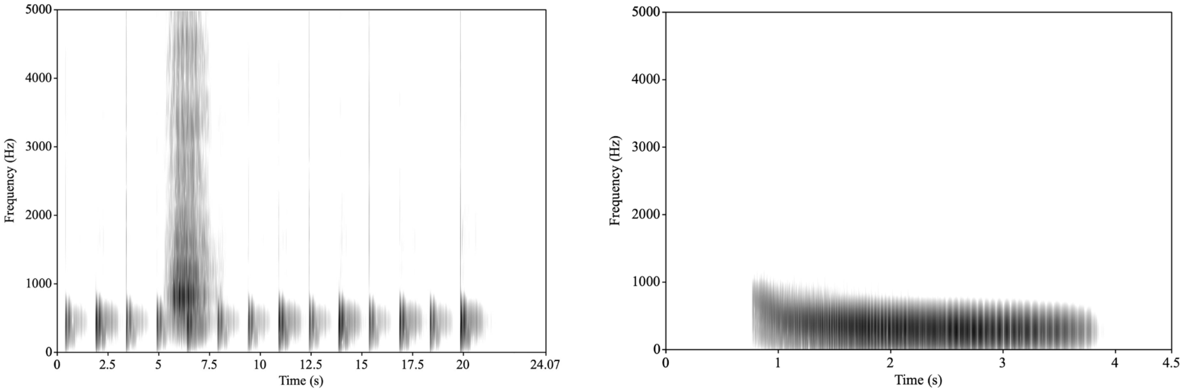
2.5.2.3. Sound validation. To prevent a design malfunction in the experiment, the sound validation process was conducted separately from the simulator evaluation, with no experimenters participating in both phases. During the validation process, participants viewed videos depicting various manoeuvres accompanied by spatial sounds. Subsequently, they were asked to complete a 7-point Likert scale questionnaire, evaluating the perceived spatiality of the sounds (how well the sound corresponded to the vehicle's direction of movement) and the level of annoyance caused by the sounds. The results are described in Section 3.1.

2.6. Secondary task

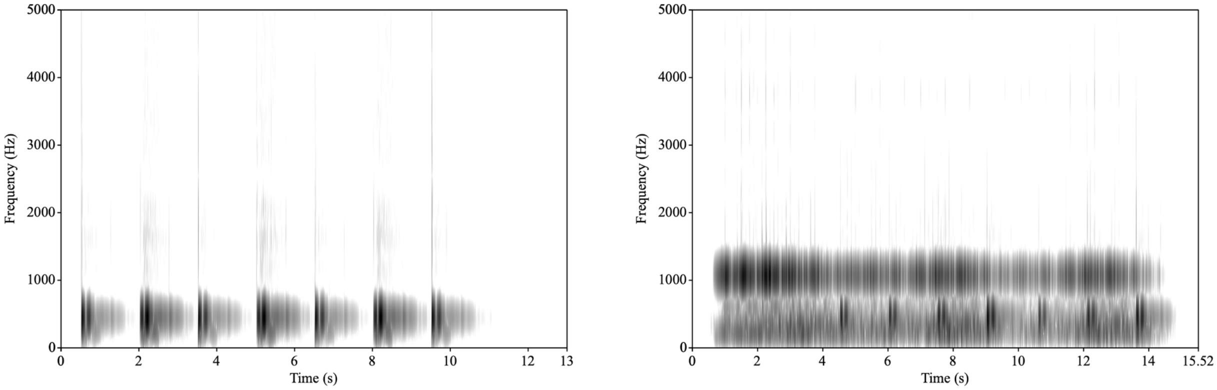
Participants were asked to perform a typing task, a visual-motor task without sound, to simulate engagement in a non-driving task during automated driving. The task was conducted using an application called 'Speed Typer-Typing Test'. The driver typed the given text without a time limit. The task is visually and cognitively demanding, self-paced and interruptible, so participants could pause it whenever they want to check the driving environment. Participants were instructed to engage in the typing task with a tablet on their lap.

2.7. Measurement

During driving, eye-gaze behaviour and situation awareness were collected. Eye gaze behaviour was recorded at 60 Hz using a smart-eye system with four infrared cameras mounted in the vehicle cockpit. We measured the percentage of time, where the eyes were on the road when participants glanced within the windshield area and the percentage of time eyes were on the automation display in



(a) Overtake (b) Slowdown



(c) Turn right (d) Roundabout

Fig. 6. Spectrogram of the spatial sound of four manoeuvres.

the centre console. This captures whether participants showed different monitoring behaviours. Situation awareness was measured with the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1988). After each manoeuvre, participants answered questionnaires related to perception, understanding and projection of the present situation (C. Nadri et al., 2021). Participants received a score of 1 if they correctly (1) perceived the situation (2) understood what was happening in the situation and (3) could predict the car's action. They could receive partial scores based on correctly answering one(1/3) or two(2/3) SA components. After each interface condition, participants answered a questionnaire regarding trust, sense of control, workload, and acceptance of the automated vehicle. Trust in automation systems was assessed using a 7-point Likert scale questionnaire based on (Jian et al., 2000) including four trust-related items (Mistrust (the system behaves in an underhanded manner), Suspicion (I am suspicious of the system's intended action or outputs), Confidence (I am confident in the system), and Reliable (The system is reliable)). The sense of control was evaluated using a 7-point Likert scale questionnaire to state whether they felt in control of the vehicle at any point during each scenario (Beattie et al., 2014). Workload was evaluated using a DALI (Pauzie, 2008) questionnaire, which is a modified NASA-TLX (Sandra G. Hart, 1988) and adapted to the driving task workload. It was deemed useful to determine the effect of different user interfaces on driver workload. Participants answered a 20-interval questionnaire consisting of six items (effort of attention, visual demand, auditory demand, temporal demand, interference, and situational stress). 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 (Laan et al., 1997). The scores for items 1, 2, 4, 5, 7 and 9 were reversed in the calculation. After all UI conditions were completed, participants were asked to rank the four types of interfaces on usefulness. Finally, in a short-constructed interview, participants answered preferences for manoeuvre information and sounds.

2.8. Procedure

Participants were welcomed and introduced to the experiment. They were asked to read the experiment information and sign an informed consent form before they filled out a demographic questionnaire (age, gender, driving experience, and visual and auditory acuity). After finishing the questionnaire, they moved into the driving simulator. Participants adjusted the sitting position according to their individual preferences, and an experimenter calibrated the eye-tracking system. Participants were informed that they would be driving a conditionally automated vehicle, with the vehicle performing lateral and longitudinal motion control while they engaged in a secondary task and did not need to intervene in driving at all if the system did not ask for take-over control. Participants drove a training session to familiarise themselves with the simulator and learn how to answer situation awareness questions while driving. This training lasted until participants could handle all tasks well. Then, the simulator experiment started. Before each UI condition, participants experienced each UI with an explanation in the training scenario to reduce the learning impact of each UI. Then, the main experiment was started. For each UI condition, participants experienced four manoeuvres in a fixed order. Participants were informed they could stop if they felt uncomfortable or experienced motion sickness. During driving, participants answered situation awareness verbally after each manoeuvre. Each UI condition took around seven minutes. After each UI condition, participants answered the questionnaire about t trust, sense of control, workload, and acceptance. This was repeated four times to experience four UI conditions. The order of four UI conditions was randomised. Participants had a break between the third and the fourth UI conditions. After four UI conditions, they answered the ranking about the preference of interfaces and had a short interview. The entire procedure took around one and a half hours.

2.9. Data analysis

Statistical analysis was conducted using IBM SPSS ver.27. The data were analysed using a separate repeated-measures analysis for each dependent factor (eye-gaze behaviour, situation awareness, trust, sense of control, workload, and acceptance) with UI as an independent factor (four levels). To analyse the effects of UI eye-gaze behaviour, situation awareness, trust, sense of control, workload, and acceptance, a one-way ANOVA was used. Effects were declared statistically significant if $\alpha < .05$. Post-hoc analysis was conducted with a Bonferroni test where the α value was adjusted by dividing it by the number of comparisons. Therefore, $\alpha = .008$ was used as α for post-hoc analysis on the effects of UI.

3. Results

Twelve participants were involved in validating the sounds prior to the simulator experiment to ensure the accuracy of the spatial sounds and prevent interface manipulation errors. Subsequently, twenty-seven participants participated in the simulator experiment to evaluate the impact of the user interfaces. None of the participants in the sound validation participated in the main experiment.

3.1. Sound validation results

A total of twelve participants, including four females, were involved in the validation of spatial sounds. The average age was 31.33 years (SD = 4.51). Sounds were rated higher than the mid-point of the 7-Likert scale on perceived spatiality (mid-point = 4, Overtake $p = .03$, Slow down $p = .04$, Turn right $p = .04$, Roundabout $p < .001$) and lower than the mid-point on annoyance (mid-point = 4, Overtake $p < .001$, Slow down $p = .04$, Turn right $p < .001$, Roundabout $p = .01$) as shown in Fig. 7. These findings indicated that the sounds communicated the spatiality of the driving situation and did not elicit significant annoyance. Based on the results, it was determined that the sounds would be suitable for use in the main experiment.

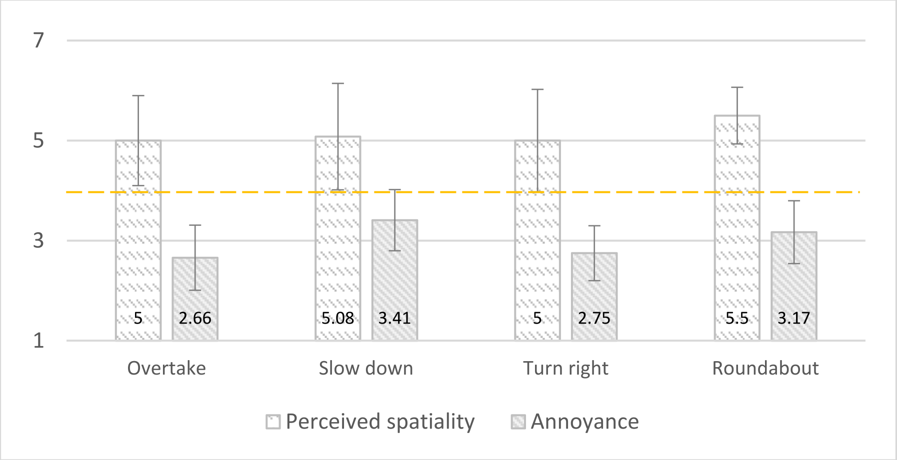


Fig. 7. Perceived spatiality and Annoyance of sounds for all manoeuvres The yellow dashed line represents the mid-point (4) (Error bars reflect standard error of the mean).

3.2. Main experiment results

3.2.1. Trust

Trust-related items' scores for the user interfaces are shown in Fig. 8. *Notification* condition received the highest trust, and *Baseline* received the lowest trust in all items ('*Mistrust*', '*Suspicion*', '*Confidence*', and '*Reliable*'). Significant differences were found between the different UI conditions for all items with a Greenhouse-Geisser adjustment. (*Mistrust*: $F(2.32, 60.40) = 7.01$, $p = .001$, $\eta^{2} = .212$, *Suspicion*: $F(2.24, 58,20) = 16.63$, $p < .001$, $\eta^{2} = .390$, *Confidence*: $F(2.26, 58.85) = 6.59$, $p = .002$, $\eta^{2} = .202$, *Reliable*: $F(2.20, 57.24) = 6.52$, $p = .002$, $\eta^{2} = .201$). Pairwise comparisons showed that the *Notification* and *Spatial sound* condition received significantly higher trust than the *Baseline* for all items.

3.2.2. Acceptance

Fig. 9 shows the mean score of nine acceptance-related items for UI conditions. Cronbach's analysis showed the high reliability between each participant's score of nine items (Cronbach's alpha = .93). The results showed that *Baseline* received the lowest acceptance. There was a significant difference between UI conditions (($F(3, 78) = 50.31$), $p < .001$, $\eta^2 = .66$). A pairwise comparison showed that the *Notification* condition was significantly higher than the *Baseline* and *Visual-only* conditions. The *baseline* received significantly lower scores of acceptance than other conditions.

3.2.3. Eye-gaze behaviour

The eye-gaze data of 18 participants out of the 27 was used in the analysis. The data of the nine excluded individuals was not used due to bad quality. The results showed that the eye-gaze behaviour did not differ over UI conditions. and was similar for the visual display and driving environment. Averaged over conditions, participants watched the road 5% of time and the UI 4% of time. Because there was a breach of homogeneity a Greenhouse-Geisser correction was used. There was no significant difference in the *ratio of gaze fixation on the display* ($F(3, 51) = 0.641$, $p = .592$, $\eta^{2} = .036$) and the *ratio of gaze fixation on the road* ($F(1.83, 31.10) = 0.568$, $p = .557$, $\eta^{2} = .032$). There was no correlation between the eye-gaze ratio on the visual UI of each participant and their situation awareness, trust, and workload.

3.2.4. Situation awareness

Fig. 10 presents the situation awareness scores for the different UI conditions. The *Baseline* received the lowest score in all manoeuvres. The *Spatial sound* condition scored the highest in the *Turn right* and *Slow down* manoeuvres and the *Notification* condition scored the highest in *Overtake* and *Roundabout*. Note that situation awareness scores reached the maximum level in the *Overtake* manoeuvre in the *Notification* condition and the *Turn Right* manoeuvre in the *Spatial sound* condition because the task was easy for participants. Significant differences were found between the different UI conditions for all manoeuvres with a Greenhouse-Geisser adjustment except *Roundabout* (*Overtake*: $F(2.12, 54.99) = 27.10$, $p < .001$, $\eta^{2} = .510$, *Slow down*: $F(2.01, 52.36) = 8.78$, $p < .001$, $\eta^{2} = .252$, *Turn right*: $F(2.08, 54.10) = 37.36$, $p < .001$, $\eta^{2} = .590$, *Roundabout*: $F(3, 78) = 12.11$, $p < .001$, $\eta^{2} = .318$). Pairwise comparisons showed that the *Spatial sound* and *Notification* conditions induced higher situation awareness scores for all manoeuvres. The *Spatial sound* and *Notification* conditions resulted in significantly higher situation awareness scores than the *Baseline* for all manoeuvres and higher situation awareness scores than *Visual-only* for all manoeuvres except for *Roundabout*. The *Visual-only* conditions

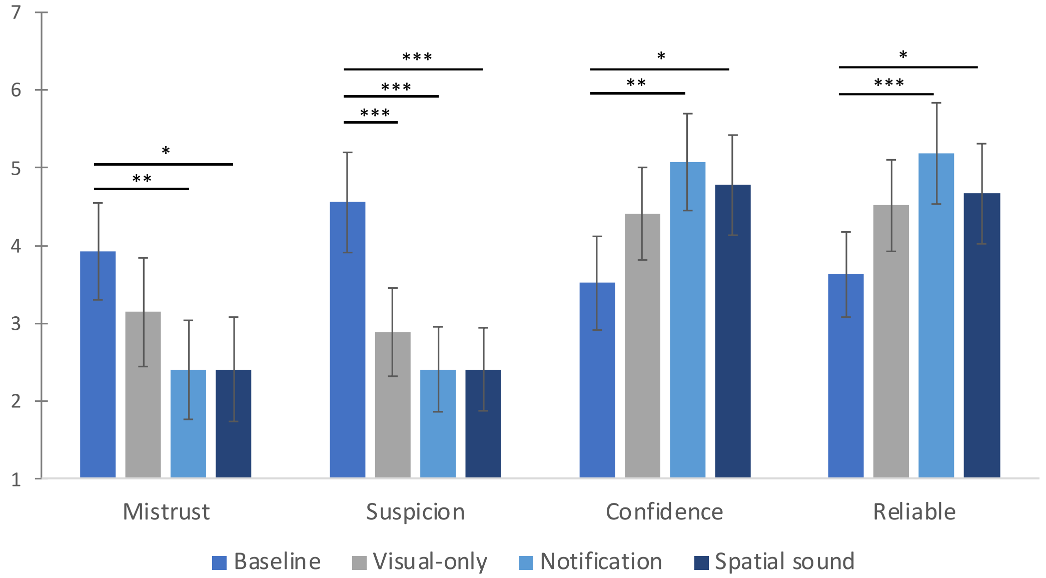


Fig. 8. Trust for UI conditions (*$p < .05$, **$p < .01$, ***$p < .001$) (Error bars reflect within-subject standard error of the mean).

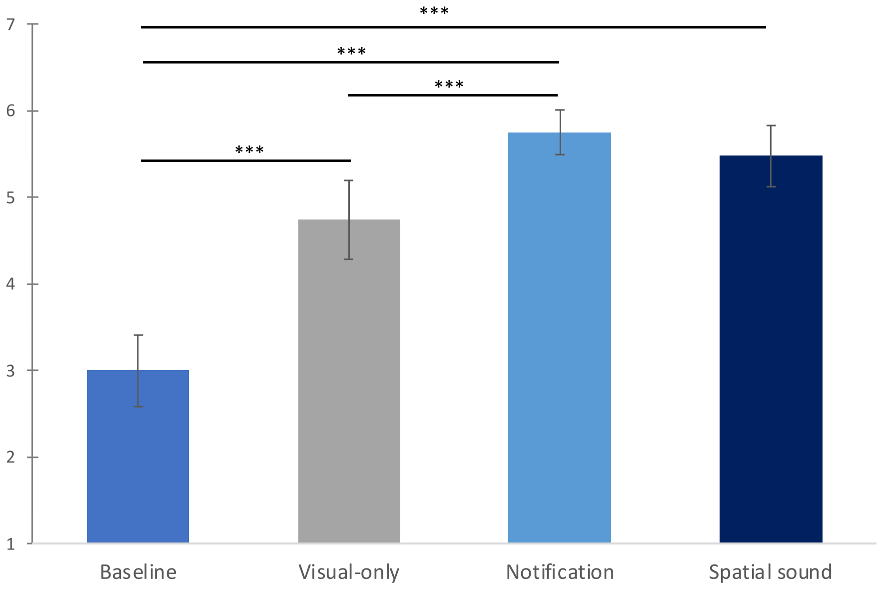


Fig. 9. Acceptance for UI conditions (***$p < .001$) (Error bars reflect within-subject standard error of the mean).

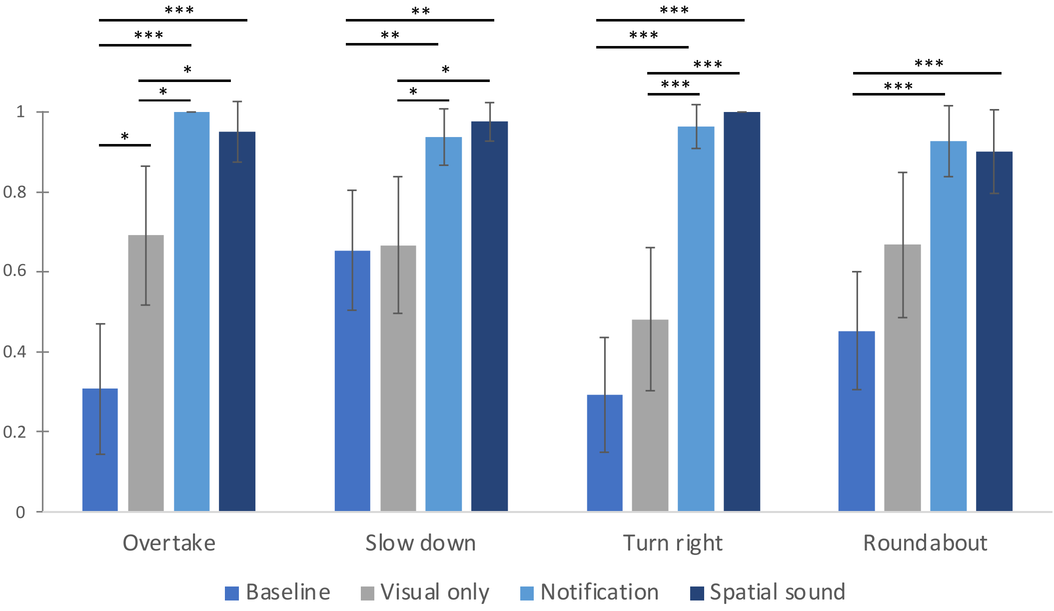


Fig. 10. Situation awareness for manoeuvres and UI conditions (*$p < .05$, **$p < .01$, ***$p < .001$) (Error bars reflect within-subject standard error of the mean).

resulted in significantly higher situation awareness scores than the *Baseline* in the *Overtake* manoeuvre. In addition, Cronbach's analysis showed the high reliability between each participant's score of SA of four manoeuvres (Cronbach's alpha = .73).

3.2.5. Workload

A summary of workload results is shown in Fig. 11. The overall workload is the average score of the six questions in DALI. Cronbach's analysis showed the high reliability between each participant's score of the six questions (Cronbach's alpha = .85). No significant main effect was found in the *effort of attention* ($F(2.15, 55.77) = 2.86, p = .099, \eta^2 = .062$), *visual demand* ($F(1.92, 50.38) = 3.00, p = .061, \eta^2 = .103$), *temporal demand* ($F(3, 78) = 0.528, p = .664, \eta^2 = .020$), *interference* ($F(3, 78) = 0.799, p = .496, \eta^2 = .030$), and *overall workload* ($F(2.20, 57.07) = 1.95, p = .148, \eta^2 = .070$). There was a significant difference in two items with a Greenhouse-Geisser adjustment: *auditory demand* ($F(1.94, 50.40) = 4.80, p = .013, \eta^2 = .156$) and *situational stress* ($F(2.25, 58.45) = 14.73, p < .001, \eta^2 = .362$). Auditory demand workload was significantly lower with the *Visual-only* condition in comparison to the *Baseline* and *Spatial*

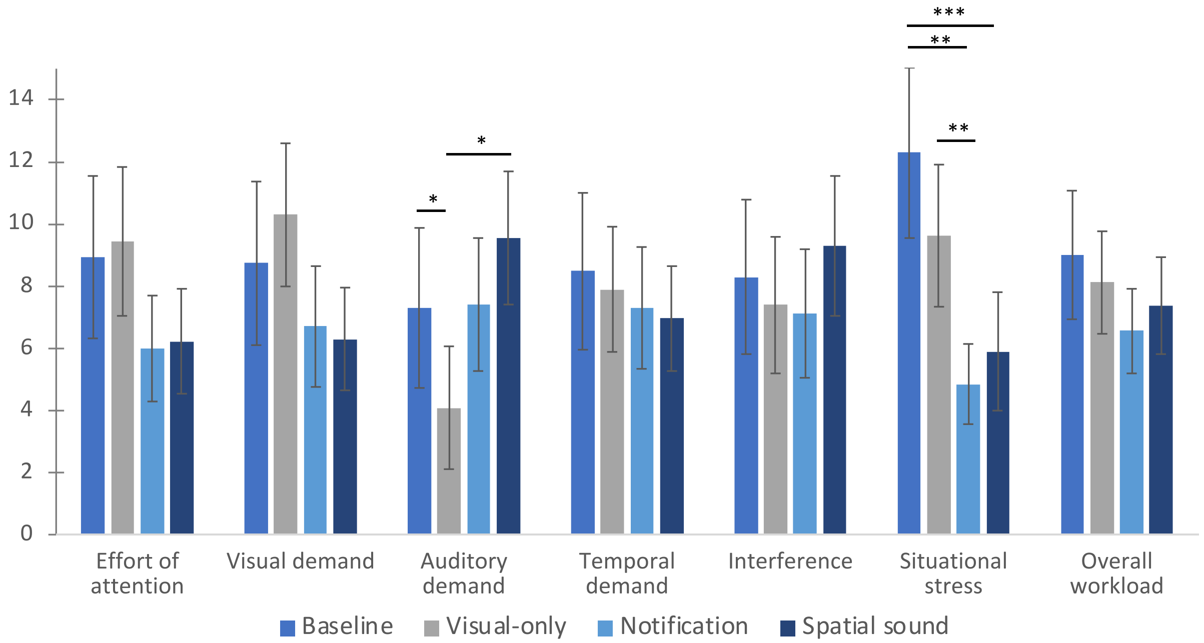


Fig. 11. Workload for UI conditions (*$p < .05$, **$p < .01$) (Error bars reflect within-subject standard error of the mean).

sound conditions. Regarding situational stress workload, the *Notification* condition was significantly lower than the *Baseline* and *Visual-only* conditions. The *Spatial sound* condition also received significantly lower scores than the *Baseline*.

3.2.6. *Sense of control*

As shown in Fig. 12, the *Baseline* received the lowest sense of control scores, and the *Spatial sound* condition received the highest scores. There is a significant difference between the different UI conditions with a Greenhouse-Geisser adjustment ($F(1.75, 45.44) = 10.33$, $p < .001$, $\eta^2 = .28$). The *Baseline* received a significantly lower sense of control scores than other UI conditions.

3.2.7. *Usefulness of UI*

Concerning the ranking of the UI usefulness, the Friedman test showed that participants ranked four conditions of UI types significantly differently ($\chi^2(3,27) = 59.49$, $p < .001$) (see Fig. 13). Post-hoc comparisons indicated that participants gave the lowest usefulness ranking when presented with the *Baseline* and the highest when presented with the *Notification* or *Spatial sound* condition. There was no significant difference in usefulness ranking between the *Notification* and *Spatial sound* conditions.

3.2.8. *Short interview*

Twenty-six out of twenty-seven participants mentioned that the UI conditions with sounds (*Notification* or *Spatial sound* condition) were useful. Regarding the feedback on auditory UIs, fifteen mentioned that the *Spatial sounds* were annoying because the duration was longer than necessary or the meaning was unclear. Only one participant mentioned that the *Notification sound* was annoying.

4. Discussion

This study investigated the impact of automation manoeuvre information on user trust, situation awareness, acceptance, sense of control, and workload. To this end, we designed four user interfaces through which information was presented via visual and auditory modalities. The results showed that providing manoeuvre information enhances trust, acceptance, situation awareness, and sense of control. Especially, presenting the information through the auditory modality showed higher ratings than when using only visual information. In addition, a marginal difference has been found between the traditional notification (beep) and the innovative spatial sound.

The results show that vehicle-to-driver communication about automated vehicle manoeuvres strongly enhances drivers' trust and acceptance in automated vehicles. The *Baseline*, which had no manoeuvre information, received the lowest trust and acceptance score. This result is analogous to (Basantis et al., 2021; Ma et al., 2021), who found that manoeuvre information increases driver trust. For our study, in particular, the high effect size of the *Suspicion* indicates that drivers distrust automation because they do not know the intention of the vehicle without manoeuvre information. The lowest acceptance in the *Baseline* may be due to the users' expectations of a modern UI design and the perception that the *Baseline* was not up to par with their expectations. This is consistent with our previous research (Kim et al., Submitted), which showed that the mere provision of a user interface providing manoeuvre information increases acceptance in partially automated vehicles. Furthermore, more elaborate information via auditory and visual modalities does not

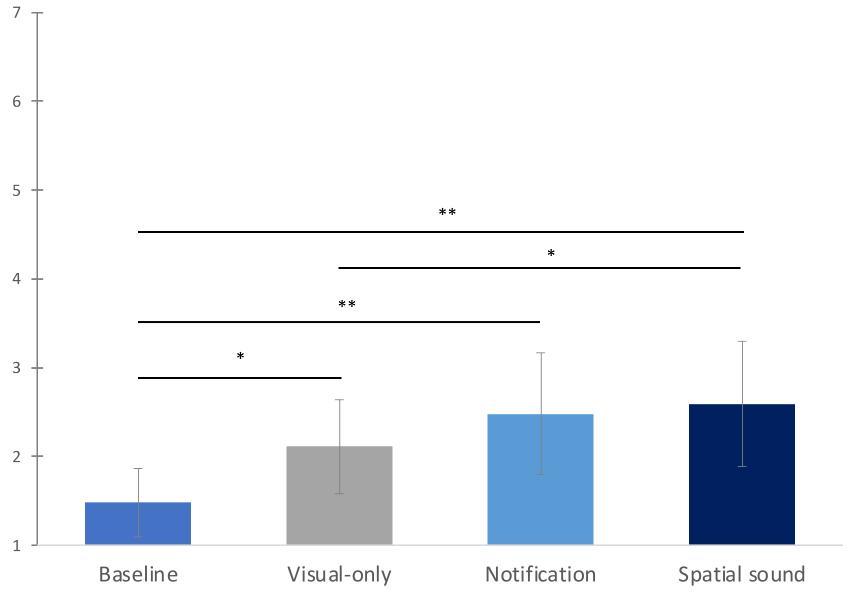


Fig. 12. Sense of control for UI conditions (*$p < .05$, **$p < .01$) (Error bars reflect within-subject standard error of the mean).

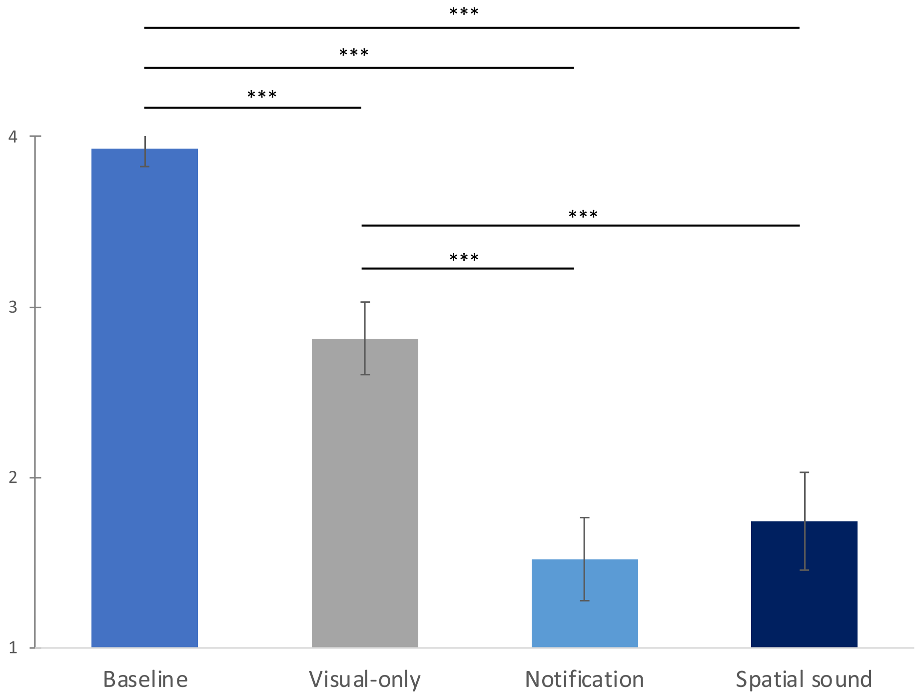


Fig. 13. Usefulness of UI ranking (1: best, 4: worst) (***$p < .001$) (Error bars reflect within-subject standard error of the mean).

significantly affect workload. Only the auditory demand workload was higher in the *Baseline* and *Spatial sound* conditions compared to the *Visual-only*. Remarkably, there is a higher auditory workload demand in the *Baseline* condition, which only provides engine sound. Perhaps participants' efforts on visual interface mitigate perceived auditory workload. On the other hand, with *Spatial sound*, auditory work may increase due to information given by spatial sounds.

The results highlight that automation manoeuvre information using the auditory modality is highly beneficial for the user experience by enhancing trust, acceptance, situation awareness, and sense of control. Especially, providing manoeuvre information via auditory modality may alleviate situational stress in automated driving. Interestingly, the effectiveness of the different auditory UI types varied depending on the specific manoeuvre. For example, the *Notification* condition received the highest situation awareness score in the *Overtake* and *Roundabout* manoeuvres, while the spatial sound performed better in the *Turn right* and *Slow down* manoeuvres. The spatial sound is preferred in scenarios where drivers are already familiar with sounds similar to spatial sounds, such as indicator sound when changing lanes or driving noise when slowing down. It is interpreted that the relatively low situation awareness of spatial sound at the *Roundabout* and *Overtake* manoeuvre is not due to the complexity of the sound but relates to how familiar sounds are in this situation. If drivers become familiar with hearing sounds in the situation, there is a possibility that the situation awareness will increase during this manoeuvre. Note that long-term sound exposure can irritate the driver (Edworthy, 1998) or increase the auditory workload (Wiese & Lee, 2004). Therefore, further research is needed to design sound scenarios for long-term sound exposure or when performing non-driving-related auditory tasks while minimising sound-related annoyance.

When comparing the *Notification* and the *Spatial sound*, no significant differences were found when combining all manoeuvres. However, the *Notification* condition appeared to be more widely accepted than the *Spatial sound* condition. Some participants expressed dissatisfaction with the *Spatial sound*, citing issues such as long durations and unclear meanings. The *Notification* (beep) is an incremental change for users, so it may be acceptable. On the other hand, the spatial sounds are considered a radical change because users have not previously been provided or become familiar, so the acceptance and usefulness ranking of the *Spatial sound* conditions was relatively low compared to *Notification*. These findings emphasise the importance of careful design in integrating auditory feedback to avoid interference and frustration for users. The principles of MAYA (Most Advanced, Yet Acceptable) introduced by Raymond Lowe (1951) have primarily been explored in the visual domain (Hargadon & Douglas, 2001), but their applicability can be extended to the auditory domain (Hekkert, 2006). Participants who are accustomed to familiar abstract sounds, such as beeps, may initially find it challenging to embrace the novelty presented by spatial sounds. Consequently, it is anticipated that users' acceptance of auditory designs will likely increase if the design successfully introduces novelty while maintaining the typicality of the sound. Achieving the balance is critical to ensure that the auditory experience remains understandable and familiar enough to be accepted by users while incorporating novel elements that engage their interest. While the learning time was short and could not be fully evaluated in the experiment, during prolonged periods of automated driving with spatial sounds, it can be possible that the driving situation can be comprehended through sound (Beattie et al., 2014; Gang et al., 2018; Wang et al., 2017) without the need for visual confirmation. This aspect is vital in keeping the driver engaged in the driving loop. Therefore, further research can address the relationship between novelty, typicality, and user acceptance of spatial sounds. Shedding light on these specific mechanisms will facilitate the development of effective strategies for improving the acceptance and integration of spatial sounds in UI for automated driving.

5. Limitations and perspectives

Some limitations of the study provide an opportunity for future research to build on the findings and explore the topic further. For example, conducting studies in real-world driving environments may provide a more accurate representation of how users interact with manoeuvre information. Additionally, exploring the long-term effects of exposure to different types of manoeuvre information can help understand how user perceptions and experiences may change over time. Furthermore, the study suggests that sound design may be an important consideration for the effective design of automation interfaces. While the study validated the sound design before the experiment, some participants still found the sounds to be annoying or ambiguous, indicating the need for more iterations and careful design considerations for sound. If there are more scenarios in which spatial sound is used, it is necessary to consider how to convey the situation as sound intuitively and whether there is no confusion between sounds. In addition, as we designed a fixed-order manoeuvre scenario, introducing a random order of manoeuvres may lead to different sound perceptions. Overall, while the study's limitations should be considered, they also highlight areas for future research and provide opportunities for further development and improvement in the field.

6. Conclusion

The study emphasises that automation manoeuvre information using auditory modality can improve the driving experience by enhancing user factors such as trust, situation awareness, sense of control, and acceptance, and indicates that it is important to carefully design sounds to avoid user frustration and ensure a positive user experience. The results underscore the importance of vehicle-to-driver communication regarding automated vehicle performance. The absence of manoeuvre information reduces trust and acceptance, highlighting the necessity of transparency in automated systems. Notably, the inclusion of auditory information, whether in the form of traditional notifications or innovative spatial sounds, amplifies these benefits, with implications for improving user experiences in automated driving scenarios. For example, imagine a scenario where a driver hears a clear and informative spatial sound when their automated vehicle is about to overtake another vehicle. This not only enhances trust in the vehicle's capabilities but also improves situation awareness, as the driver precisely understands the vehicle's intentions. Additionally, we have revealed nuances in the effectiveness of auditory user interfaces across different driving manoeuvres. This knowledge can guide the selection of interface types based on user familiarity and situational context. Furthermore, the study raises important considerations for the integration of auditory feedback, emphasising the need for designs that strike a balance between novelty and familiarity to ensure user acceptance and usability. Overall, this study contributed to understanding the impact of the manoeuvre information and auditory user interface in automated driving, with potential implications for improving the design and acceptance of automated vehicle interfaces in the future.

CRediT authorship contribution statement

Soyeon Kim: Conceptualization, Methodology, Data curation, Formal analysis, Validation, Visualization, Writing – original draft. **René van Egmond:** Supervision, Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Riender Happee:**

Supervision, Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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