Sound and vision: how can auditory displays support supervision of automated driving?

Canmanie T. Ponnambalam, Rins de Zwart, & Reinier J. Jansen
SWOV Institute for Road Safety Research
The Netherlands

Abstract

Higher levels of vehicle automation allow for less constant attention on the driving task, enabling drivers to engage in non-driving related activities (NDRAs). Shifts between levels of automation require self-regulation of NDRA engagement to remain sufficiently attentive for future changes in automation level. A visual HMI can provide information about current and upcoming changes in automation level but requires visual attention, compromising the convenience of automation. Auditory displays have been used to provide continuous information during monitoring tasks, but research into how sound can aid automation supervision in the driving context is limited. This online video study explored how auditory displays can augment a visual HMI of a self-driving vehicle while participants were engaged in an NDRA, comparing sounds that convey information about current and (time to) future system states through changes in volume, inter-pulse interval, harmonic series, and pitch. Adding sound improved perceived direction of change and remaining time until changes in automation level. Despite best efforts in sound design, sounds in the vehicle were initially perceived as negative even when they indicated something positive such as an upcoming increase in automation level. This and other implications for HMI research and design are discussed further.

Introduction

The mass adoption of highly automated vehicles promises many gains such as safety benefits, improved productivity, and lower adverse impacts on the environment (Greenblatt & Shaheen, 2015; Tafidis et al., 2022). However, it is largely accepted that the transition period will include the introduction of partially automated vehicles that will require a human driver to be present and available to take control of the vehicle under certain circumstances. This transfer of control between the automated vehicle and human driver is a safety critical task requiring a timely and effective takeover, during which the human must remain attentive and have suitable situational awareness.

Existing literature into auditory displays for supervision of automated driving often centres around the moment of transfer, with less attention given to how the driver can

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be supported in the time leading up to this safety-critical point (de Winter et al., 2021). Transitions between different automation levels can occur not only when takeover is required, but also when moving between levels of automation that have different requirements of the driver (Lu et. al., 2016). With increasing data and improved technology, it will be possible to give advance notice on when some transitions are expected. For example, in the case where a vehicle is following a given route and will shift to a lower automation level when the vehicle leaves the highway and enters an urban area. This lower automation level will require the driver to have their eyes on the road. In such scenarios, information can be provided to the driver to help them self-regulate their engagement in non-driving related activities. Solís-Marcos et al. (2018) found that performance on a visual non-driving related activity (NDRA) decreased during automated driving compared to manual driving. The authors suggest that the supervisory task required in the automated driving condition (i.e., frequently looking at a system state symbol) was more disruptive to NDRA performance than controlling the vehicle in the manual driving condition, which supports research into how to make monitoring as non-demanding as possible. Previous work has looked at the use of visual displays to enhance situational awareness of drivers during automated driving by providing cues about automation level and time-to-takeover request (Tinga et al., 2022).

The present study investigates how auditory displays can be used in addition to visual displays to assist drivers (who may be occupied with NDRAs) in maintaining mode awareness and conveying time budget. Research has shown that sound displays can be highly beneficial during monitoring tasks, particularly when visual attention is compromised (Hermann et al., 2011, Nees & Walker, 2011). In increasingly automated vehicles, sound is becoming an important signal for crucial time-imminent information (e.g., blind spot monitoring, collision warnings), however it remains underutilized in delivering non-crucial but important information.

An online video study was conducted to investigate the benefits a sound display can provide to a visual information system that aids the driver in supervising autonomous driving. Several studies have proposed different properties (e.g., pitch, volume) of auditory signals that can convey concepts such as time and uncertainty. Research has shown that higher urgency and lower time budget can be communicated by increasing pitch (Baldwin & Lewis, 2014; Ko et al., 2021) or decreasing the inter-pulse interval between signals (Baldwin et al., 2012; Baldwin & Lewis, 2014; Nadri et al., 2021; Song et al., 2022). Pitch has also been used to indicate different severity levels in a medical patient monitoring system (Andrade et al., 2021), indicating the potential to communicate different levels of functioning. In terms of spectral composition, Edworthy et al. (1991) found that sounds with a regular harmonic series (e.g., all harmonics are integer multiple of the base frequency) were experienced as less urgent than sounds with an irregular harmonic series (e.g., non-integer multiples). Furthermore, Gray (2011) has shown that volume increase during playback (e.g., looming) can be used to communicate time-to-collision, resulting in a faster brake response time. Given their promise in past studies, the present study will investigate parameter manipulation in pitch change, volume, harmonic series, and inter-pulse interval in communicating direction of change of automation level and time budget. No studies were found that investigate the use of sound in the non-takeover autonomous driving-monitoring context considered here. This study aims to answer the following two questions: 1) Does an auditory display provide additional support to a visual display in conveying upcoming changes in automation level? 2) Is there an added benefit to manipulating pitch, harmonics, and inter-pulse interval in conveying these upcoming changes?

Method

In a previous study, different visual displays were evaluated based on how well they communicated automation level, upcoming changes to automation level, reasons for the change, and remaining time until said change (Tinga et al., 2022). The present study builds on these results by incorporating an auditory display into their recommended visual display and by investigating different types of sound signals to see which best support a visually distracted supervising driver. An online user study was designed consisting of a self-guided survey with embedded videos. In the survey, participants watched videos that placed them in the driver's seat of a partially automated vehicle while it is driving itself (see Figure 1). The visual information system uses emoji-type icons to display information on the current and upcoming automation level when a change is pending. A bar that lights up across the dashboard indicates when a change is upcoming; the depletion of the bar indicates the time remaining until said change. Sound was presented when the vehicle is 60 seconds away from an upcoming change (the moment the bar appears), 30 seconds away, and 10 seconds away. The study was approved by the ethical board of SWOV – Institute for Road Safety Research.

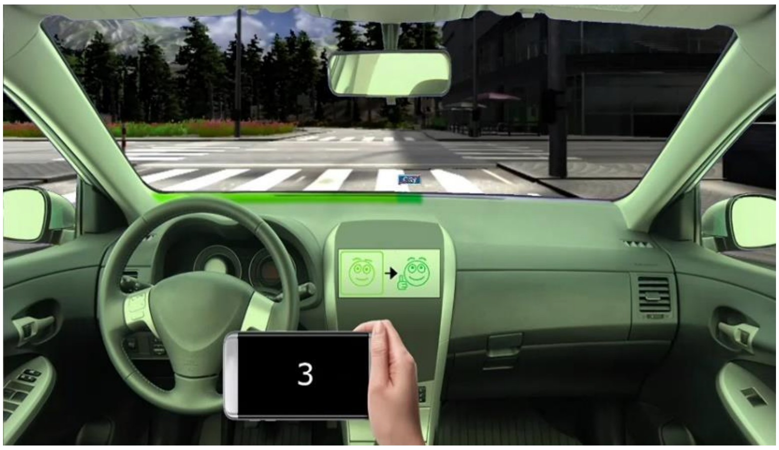

Figure 1. A screenshot from one of the videos included in the study (adapted from (Tinga et al., 2022)). The smiley face icons indicate the current automation level and the upcoming change, and the green progress bar indicates time remaining until the change. Participants monitored the driving while counting the number of times a "4" appeared on the mobile phone.

Participants

Participants were recruited via Prolific (https://prolific.co), a commercial web-based tool for participant recruitment considered to produce high data quality in comparison to other platforms for online behavioural research (Eyal et al., 2021). As the survey is in English, English fluency was a requirement, in addition to having a valid driver's license and owning a car. Participants were recruited only from the European Union or United Kingdom, where the road signs are consistent with those visible in the interface. They were required to continue with the study only if they were using a laptop or desktop computer, and not a mobile or tablet device.

In total, 200 people completed the study in full. Of these, four were rejected due to concerns about data quality related to the speed at which they finished the study and/or the low-effort responses received. Participants were paid at a rate of £9.90/hour. On average, the study took 18 minutes to complete. The participants were gender balanced, with 97 identifying as male, 96 identifying as female, 2 identifying as non-binary and 1 preferring not to identify. The mean age was 31 years (range: 19-73, SD = 10.3).

Sound Sets

This study investigates whether sounds encoded with information can provide intuitive understanding in support of a visual HMI, particularly when drivers are visually distracted. The body of research on auditory display design for supervision tasks is dwarfed by that focused on alarms and warnings. In the latter, three main types of signals have been investigated: auditory icons, earcons and speech or speech-based sounds. In attempt to combine the intuitiveness of auditory icons with the flexibility of earcons, an *echo* metaphor was designed to communicate the time until a change in automation level. In an echo, the time it takes for the sound to return, and the volume of the returned sound are indications of distance to the reflecting surface. This is an intuitive concept that may help to communicate the time until a change in automation reliability. To communicate the direction of change in automation level, an increase in pitch is used to indicate an increase in level (i.e., higher level of automation). Additionally, inharmonic tones may be experienced as a machine that is not running smoothly. This study examines whether this metaphor can be used to communicate a transition from or to a lower level of automation reliability. To isolate the effects of manipulations of these parameters, three sound sets were designed in Max (v8.3.1) that share properties as much as possible and build up with increasing complexity in terms of the manipulated parameters: 'basic', 'simple', and 'complex'. The 'basic' set is a single tone with an exponential decay. The 'simple' set contains two tones where the pitch and inter-pulse interval are manipulated to indicate whether automation level is going up (more automated) or down and in how long. In the 'complex' sound set, the pitch and inter-pulse interval as well as the harmonics and volume are manipulated. The sounds and their detailed descriptions can be found at: https://github.com/canmanie-swov/HMI_sound_study. A fourth 'silent' sound set did not include sound. Figure 2 provides a graphical depiction.

Experimental Conditions

The direction of an upcoming change in automation level (e.g., 'up' or 'down') was manipulated in addition to manipulating the sound set. Thus, a 4 (Sound set) $\times$ 2 (Direction) within-subjects experimental design was conceived, corresponding with a total of 8 experimental conditions. To restrict the total duration of the experiment, each participant was presented with 4 conditions, with the constraint that all sound sets were experienced once and that each direction of change in automation level was experienced twice. Participants experienced the sound sets in a random order. A ‘down’ drive was always followed by an ‘up’ drive and vice versa.

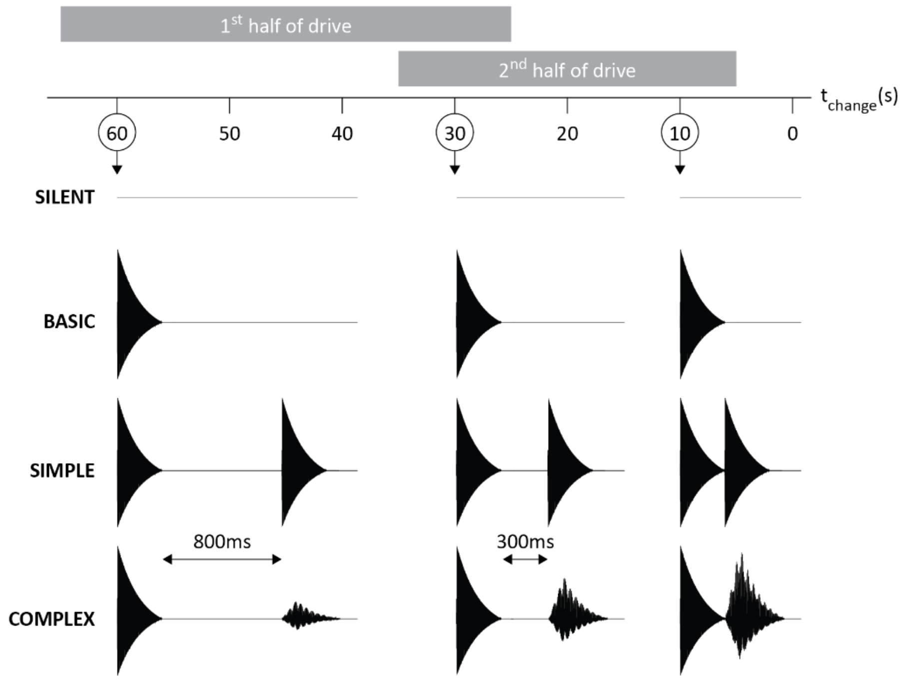

Figure 2: Timeline of each drive, divided into two halves presented separately. Four sound sets were available. Sounds (visualized here as waveforms) were presented at 60s, 30s and 10s before the upcoming change in automation level. The drive halves ended 25s and 5s prior to the change.

The drives corresponding to each experimental condition were split into two halves, the first half (duration: 40s) containing sounds at 60s and 30s until a change of automation level, and the second half (duration: 30s) containing sounds at 30s and 10s until a change (Figure 2). Experimental conditions featuring the ‘silent’ sound set did not include sounds throughout the drive. Each participant watched 8 videos in throughout the experiment: two drive halves by four different sound sets.

Non-Driving Related Activity (NDRA)

In a rapid serial visual presentation task, participants keep track of the number of times a target appears on the screen (Lee et al., 2006). This activity has no manual or physical component and does not require interaction with the system or an experimenter during the experiment, fitting with the online self-guided nature of this study. For this study, a single digit was visible for 500ms at 1000ms intervals, and the participants were asked to keep track of the number of times a “4” appeared in a random sequence. The NDRA was present in every drive and condition and participants were instructed to complete it to the best of their ability.

Questionnaires

At the beginning of the study, participants answered demographic questions and questions about their driving experience and experience with partially automated vehicles. After each sound condition, participants scored their subjective demand according to three dimensions of the NASA Task Load Index (TLX) (Hart & Staveland, 1988): temporal, mental and frustration. They also answered questions related to the sounds heard in the videos, particularly about how noticeable, annoying, complex, understandable, and appropriate they found the sounds.

Procedure

After providing informed consent and filling out the pre-drive questionnaires, participants were shown the same 45-second familiarization video consisting of the car driving in the environment with a pending decrease in automation level due to upcoming road work. The instructions for the NDRA were given and participants were shown another 15-second drive with the NDRA present, then asked how many times they counted the target appearing. This was followed by an audio check with a test tone at 3 dB below the volume of the stimuli to ensure that participants had functional speakers that were set at a comfortable volume. They were instructed not to adjust their audio settings beyond this point for the remainder of the experiment.

Initially, no information was given about the visual or auditory information systems present in the vehicle. The video of the first half of the first drive was presented, and participants were asked *"What do you think the information system is indicating? Choose your best guess."* With four multiple-choice options relating to a vehicle error, automation error, takeover request, or automation level change (the correct answer). It was then revealed that the vehicle contains an information system that communicates the automation level, and the time remaining until the change. After this information was given, participants were asked how soon (in seconds) they felt the upcoming change would happen. The video of the second half of the drive was then shown, and participants were asked whether they thought the automation level was going to go up or down and, again, in how many seconds, see Figure 3.

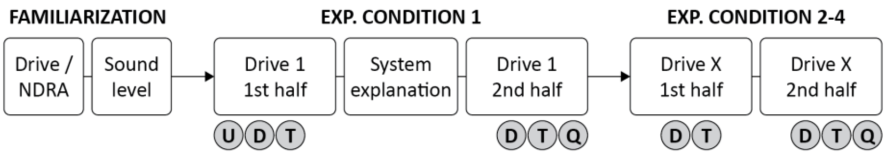

Figure 3: Schematic representation of the experimental procedure. Measures are depicted in gray circles. U = Intuitive understanding, D = Direction of upcoming change in automation level, T = estimated time until change, Q = Questionnaires on task load, usability and user experience.

In the remaining experimental conditions (2-4) the videos (6 in total) were accompanied by the sentence explaining the information system. After each video participants were asked if they thought the automation level was going up or down and in how many seconds. At the end of each experimental condition (including the first one), participants completed the adjusted TLX, questions on usability and user experience.

Results

Analysis was performed using R. All reports of significance are compared against an alpha of .05.

Understanding of direction of change

A measure of intuitive understanding was compared between-subjects, investigating the effect of sound set on whether participants answered the question "What do you think the information system is indicating?" correctly. This question was asked only once (before participants were given an explanation about the system). The results of a chi-square test are significant ($\chi^2(1) = 7.80$, $p < .05$, Cramer's $V = .52$). However, pairwise comparisons with Bonferroni correction do not reveal significance between any pairs of sound sets. Only in the 'silent' (53%) and 'simple' (60%) conditions were most participants correct. Participants were 35% and 41% correct in the 'complex' and 'basic' conditions, respectively.

Binomial logistic regression was used to investigate the relationship between sound condition and whether participants gave the correct answer when asked in which direction automation level was going to change (either 'up' or 'down'). An additional First predictor (here, and in analyses below) was a binary flag indicating whether it was the first experimental condition (where information about the system was only given halfway, see Figure 3) to distinguish between intuitive understanding and understanding after having been given a system explanation. A Direction predictor indicated whether the actual transition was up or down. The model included participant as a random effect. Initially a full factorial model was tested. In the revised model, shown in Equation (1), only significant effects were kept.

$$Direction_{Correct} = Direction + First + Direction{:}First + Direction{:}Sound\_set + (1|Participant\_ID) \quad (1)$$

The corresponding ANOVA yielded significant main effects of Direction ($\chi^2(1) = 13.32$, $p < .001$) and First ($X2(1) = 50.71$, $p < .001$). When Direction was 'down' the proportion of correct answers was significantly higher (76%) than when Direction was 'up' (66%). In the first experimental condition fewer correct answers (58%) were given than in subsequent experimental conditions (76%). The interaction between Direction and First was significant ($\chi^2(1) = 34.90$, $p < .001$), showing fewer ($\beta = -1.91$) correct responses when Direction was 'up' and First was 'true' compared to 'up' and 'false', respectively, $z = 9.20$, $p < .001$. Finally, the interaction between Direction and Sound set was significant ($\chi^2(6) = 15.31$, $p < .05$). Pair-wise comparisons showed that participants showed more ($\beta = 1.69$) correct responses when Sound set and Direction were {'complex','down'} than {'complex','up'}, $z = 5.64$, $p < .001$. Likewise, participants showed more ($\beta = 1.14$) correct responses when Sound set and Direction were {'simple','down'} than {'simple','up'}, $z = 4.01$, $p < .01$. Thus, participants were more likely to answer correctly when Direction was 'down', except with the Silent and Basic sound sets.

Time Estimates

Participants estimated how much time was remaining before the automation level would change when the true answer was 25 seconds and 5 seconds. A poisson regression model investigated the relationship of Sound set, Actual (time remaining, a categorical value of either 25 or 5 seconds) and First (experimental condition) on how far time estimates deviated from the actual time remaining. Next to these main effects, the model included an interaction between Sound set and First, as well as participant as a random effect. Data were shifted so there were no negative values. Again, the revised model, shown in Equation (2), included only significant effects. In this model, only Actual was a significant predictor (χ^2 (1) = 729.29, $p < .001$).

$$Deviation\ = Actual + (1|Participant\_ID) \quad (2)$$

The percentage of videos in which participants correctly guessed that time budget was decreasing (i.e., the second time estimation was lower than the first time estimation) was 56% in the 'silent' sound set, 59% in the 'basic' sound set, 62% in the 'simple' sound set and 68% in the 'complex' sound set. The effect of Sound set on whether participants estimated that the time budget was decreasing was initially investigated with a full factorial binary logistic regression model, with First (experimental condition) and Sound set as predictors, and with participant added as a random effect. Equation (3) describes the revised model, including only significant effects.

$$Decreased\ = First + Sound\_set + (1|Participant\_ID) \quad (3)$$

The ANOVA of the model showed that First (χ^2 (1) = 17.07, $p < .001$) and Sound set (χ^2 (3) = 20.62, $p < .001$) were significant predictors. When First was 'true', significantly fewer (β = -.62) participants indicated a decreasing time budget than when First was 'false', z = 4.12, $p < .001$. Pairwise comparisons showed that the 'complex' sound set was associated with a significantly higher likelihood of a decreasing time budget than the 'silent' sound set (β = .82, z = 4.40, $p < .001$) as well as the 'basic' sound set (β = .58, z = 3.11, $p < .05$).

Within the instances where participants correctly estimated that time was decreasing, the gap between their time-estimates was closest to the correct time of 20s (i.e., the elapsed time between 25s and 5s prior to the automation level change) in the 'basic' sound set (M = 18s), in which the single tone notably does not include timing information. The gap in the 'complex' sound set deviated most from the target gap (M = 11s), with means of the 'silent' and 'simple' sound sets being both 14s.

Questionnaires

ANOVAs were performed on the NASA TLX scales, using sound set and order as independent variables. Sound set did not yield significant results. However, significant effects of First showed that workload was experienced as higher in the first experimental condition than in subsequent conditions on mental load (F(1,776) =

11.69, $p < .001$), frustration ($F(1,776) = 4.77$, $p < .05$), as well as on temporal load ($F(1,776) = 12.05$, $p < .001$). A significant interaction effect between First and Sound set ($F(3,776) = 4.65$, $p < .01$) showed that the effect of First on temporal load was mainly driven by the 'complex' and 'silent' sound sets. These effects of First can be expected as participants were given information about what the HMI communicated after the first half of the first video.

The usability and user experience questions were answered on a 5-point Likert scale and analysed for influence of Sound set with a Kruskal-Wallis test, in which no significant impact was found. Median responses are reported only if the result of a Wilcoxon signed rank test for significant deviance from the neutral position was significant. For all sounds, participants generally noticed them (median response = "Strongly agree") and felt it was obvious why they occurred (median response = "Agree"). The median response to the question "I found the sound notifications unnecessarily complex" was "Disagree" in only the 'basic' and 'simple' sound sets. And only in the 'basic' sound set were participants more likely to be in the direction of disagreeance for the question "I would shut off the system in my own car".

Discussion

The findings show that on first exposure to the information system, sound did not improve intuitive understanding regardless of the manipulated sound parameters. In fact, all sound sets evoked an association toward negative change (automation level going down). The most common usage of auditory signals within a vehicle is to indicate an issue or alert the driver some action is needed. Participants might have assumed this was the case and expected a system failure or takeover request to be the cause of the sound, instead of the intended message of upcoming automation level change. Further investigation is needed to determine if more complex sound designs are effective as well as which natural responses may be impacting the intuitive understanding of different sound manipulations.

Participants were most likely to understand that time budget was decreasing in the 'complex' sound set, particularly when compared to the 'basic' and 'silent' sound sets. Contrary to the latter sound sounds, time budget was explicitly encoded in the 'complex' sound set (through manipulation of inter-pulse interval). The 'simple' sound set also included this information, but performance increase compared to the 'silent' and 'basic' sound sets was non-significant. These results suggest sound could be an effective way to convey decreasing time budget, but more complex sound design may be needed than mere manipulation of inter-pulse interval. Interestingly, participants were closest in their estimate of a decreasing time gap in the 'basic' sound set. In one previous study, it was found that a single master alarm (such as in the 'basic' condition) was no worse than information-rich auditory icons in reaction time and accuracy (Cummings et. al., 2007). The present study hints that there may be some factors which can be communicated effectively through sound (time budget is decreasing), and others (how much time is available) that are better communicated by a visual HMI, supporting the idea that both should be used harmoniously.

Some studies have warned against the use of auditory feedback in vehicles that may increase distraction or load (Donmez et al., 2006, 2007). While no main effect of

Sound set on the NASA TLX was found, participants indicated that they were more likely to shut off the system in their own car in both the simple and complex sound sets, suggesting that there may be room in sound design to find an effective trade-off between increasing load with providing information.

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