What's Around the Corner? Enhancing Driver Awareness in Autonomous Vehicles via In-Vehicle Spatial Auditory Displays

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ABSTRACT
There is currently a distinct lack of design consideration associated with autonomous vehicles and their impact on human factors. Research has yet to consider fully the impact felt by the driver when he/she is no longer in control of the vehicle [12]. We propose that spatialised auditory feedback could be used to enhance driver awareness to the intended actions of autonomous vehicles. We hypothesise that this feedback will provide drivers with an enhanced sense of control. This paper presents a driving simulator study where 5 separate auditory feedback methods are compared during both autonomous and manual driving scenarios. We found that our spatialised auditory presentation method alerted drivers to the intended actions of autonomous vehicles much more than all other methods and they felt significantly more in control during scenarios containing sound vs. no sound. Finally, that overall workload in autonomous vehicle scenarios was lower compared to manual vehicle scenarios.

Author Keywords
Autonomous vehicles; in-vehicle spatial auditory displays; audio; driver awareness; driving simulators

ACM Classification Keywords
H5.2 User Interfaces: auditory non-speech feedback, evaluation/methodology

INTRODUCTION
There is an increasing trend towards the development of autonomous and semi-autonomous vehicles in current vehicular research [24]. Some notable proponents of this work include car manufacturers such as Mercedes-Benz, Audi and General Motors, as well as Google and their driverless car built in conjunction with Stanford University [3]. Primary driving task automation can be considered beneficial as it has the ability to reduce the mental workload for drivers to a point where they simply monitor the systems operating the vehicle [17]. However, this reduction in mental workload is not without trade-offs. Vehicles without automation require a human to be in control of the primary driving functions at all times. Because of this requirement, the driver has a constant connection with the vehicle and is continuously updated with feedback relating to the primary driving tasks; steering, gear changing, acceleration, braking etc. This feedback loop ensures that the driver understands what actions are necessary to perform during particular driving situations [27]. In their present form, autonomous vehicles do not provide this same feedback loop as their manually controlled counterparts. As a result, there is a distinct lack of feedback provided to drivers relating to traffic situations and evasive manoeuvres. Furthermore, it has been found that an autonomous vehicles driving style is unnatural in comparison to a manually controlled vehicle [12]. Driver awareness suffers without information relating to whether or not the vehicle understands, and has accounted for, particular traffic situations. This lack of feedback is a direct result of the control shift introduced by autonomous vehicles [5]. Although research is currently focused towards the computerised operation of an autonomous vehicle [3], it is important that the next step in autonomous vehicle research looks at how to address the impact on human factors. Therefore we believe, as a starting point that an autonomous vehicle should provide a level of feedback similar to that of a manually driven vehicle. Doing so may ensure that the shift in control introduced by autonomous vehicles is diminished. Additionally, driver awareness of the vehicles actions may increase and in turn provide a more satisfactory driving experience.

The use of auditory in-vehicle displays is well documented in their ability to provide information related to secondary driving tasks e.g. SATNAV, in-vehicle entertainment,

NordiCHI '14, October 26 - 30 2014, Helsinki, Finland
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http://dx.doi.org/10.1145/2639189.2641206

parking-sensors etc. However, existing in-vehicle technologies have yet to use sound to its full potential for information display [18]. The nature of an autonomous vehicle is to provide safe operation of the primary driving tasks. Because human operation is not necessary, it may be possible to present auditory information 3-dimensionally without safety concerns. We believe a spatial auditory display may be an effective way to use sound as means of enhancing driver awareness to the intended actions of an autonomous vehicle. This auditory display could also be used to re-establish a sense of control to drivers.

In this paper we present a driving simulator study that attempted to determine the effect different audio presentation methods have on drivers of autonomous vehicles. More specifically, sounds relating to primary driving tasks (acceleration/indication/braking etc.) were presented using 5 different auditory presentation methods. The study investigated:

- User preferences towards our different auditory presentation methods to determine which is the most preferred;
- Whether spatialisation can enhance driver awareness of the intended actions of an autonomous vehicle;
- Whether auditory spatialisation assists in re-establishing a sense of control to drivers in autonomous vehicles.

This paper describes the first-known attempt to investigate whether in-vehicle auditory feedback is important to drivers in autonomous vehicles.

RELATED WORK

Vehicular Automation

The National Highway Traffic Safety Administration (NHTSA) [19] of The USA has recently disclosed a policy on automated vehicles. This document highlights the main research directions the US Government aims to address and establishes 5 separate levels of vehicular automation. The information contained within this document serves as an appropriate means to discern vehicle automation levels with respect to an influential government's guidelines. While automated vehicles are still in their infancy, it is clear that the levels of automation set out by NHTSA's document are informed and could be used to design auditory feedback. We have included a summarised table of the automation levels (see Table 1). It is important to note that the levels of automation used within this study are level 0 and level 4 therefore levels 1, 2 and 3 have been heavily summarised. These extremes we hoped would give us clean and clear results unlike levels 2 and 3 which are currently deployed in a non-uniform way across car vehicles. Also, others are investigating levels 2 and 3; the NHTSA's current research for example is expected to address vehicle automation levels 2 and 3. We believe that by comparing levels 0 and 4, our findings can be used to inform the design of auditory displays for vehicles that feature automation levels 2 and 3.

The NHTSA's document [19] discusses the necessity of undertaking research aimed at addressing the issue of human factors relating to autonomous vehicles. Their goal (NHTSA 14 – 13, May 2013, p. 6) is to develop driver-vehicle interfaces (DVI) that ensure a safe transition for drivers when switching between automated and non-automated vehicle control. They also seek to address how to effectively communicate any additional information relating to safe vehicle operation.

Automation Level	**Driver/Vehicle Expectations**
Level 0 No Automation	• Driver has control of all primary vehicle controls • Examples include systems only providing warnings (auditory/visual) and automated secondary control (e.g. wipers)
Level 1 Function Specific Automation	• Automation of **ONE** or more specific primary control functions • Driver can cede limited authority over one primary control (e.g. adaptive cruise control)
Level 2 Combined Function Automation	• **TWO** or primary control functions designed working in unison to relieve driver of control • Driver available for control at all times at short notice (e.g. lane departure warning)
Level 3 Limited Self-Driving Automation	• Driver cedes control of **ALL** primary driving functions under certain traffic/environmental conditions • Driver available for occasional control – with sufficient transition time
Level 4 Full Self-Driving Automation	• Vehicle performs **ALL** safety critical driving functions • Driver only providing destination input • Driver not expected to be available

Table 1 - NHTSA's Driver Automation Levels

In concurrence with advancements in desktop and mobile computing power, in-vehicle computing has now reached a stage where there is an ever-increasing trend towards the automation of multiple vehicle functions/systems [28]. Because of this trend, a number of limited automation functions are now readily available in modern vehicles [10]. Many new high-end luxury cars now feature the functions and systems pertaining to level 2 automation. This would include any vehicle that may provide adaptive cruise control with the added feature of lane keeping for example. Due to the pace of technological advancement in vehicle automation, many car manufacturers are already developing prototype level 3 vehicles [10]. It is therefore necessary to look beyond level 3 automation; and assess what are the future requirements with respect to the human factors of autonomous vehicle research and development.

Presentation Modality

As regards alerting a driver to what the vehicle is currently doing we chose to investigate audio presentation only. This is not to say that other modalities could not also be studied or that other modalities or indeed multiple modalities could not be used to inform a driver. In this regard Cao et al. [7] investigated the use of audio and tactile cues to convey four different levels of urgency to a driver. They presented a number of pulses and inter-pulse-interval that they manipulated to signify urgency. Politis et al.'s [22] paper describes an experiment they undertook that evaluated various multimodal combinations to warn drivers under two contexts of situational urgency: a lead car braking and not braking. Our research differs as it is focused on providing a continuous level of feedback as regards the vehicles current driving situation; therefore we selected audio as it is currently the main modality that provides feedback to a driver in vehicles.

Auditory Driver Vehicle Interfaces

As a medium for vehicle feedback, sound has a unique ability to quickly convey information and is often used in vehicles to compliment a particular visual cue or provide feedback for actions to be conducted by the driver. Within a car, sound can be used to notify the driver to a variety of events. These events may be mechanical and electrical notifications, non-primary driving information (e.g. GPS navigation), and safety critical alerts (e.g. collision warnings from Advanced Driver Assistance Systems (ADAS)) [28]. Sound is also a key feature related to the primary driving tasks; acceleration, braking, gear changing and indicating. It is often used as a means of branding by manufacturers where sounds are tailored to provide a particular sound "signature" [21]. The manipulation of certain sounds can convey a particular vehicular concept such as performance or luxury whilst still presenting clear and concise information to drivers.

An auditory in-vehicle display must convey a sense of needed action and should lead to the correct and same reactions by any user [26]. This is achieved by ensuring any sound used elicits an emotional or affective reaction when heard. For example, the perceived emotional response from a warning sound must ensure that the corresponding action is prompted immediately [9]. This is in keeping with the perception that auditory in-vehicle displays are more advantageous in their use over vision-based displays when rapid response times are necessary [15]. For instance, in a comparative study by Scott & Gray [23], the use of auditory feedback was preferred by users in comparison to visual and tactile feedback for rear-end collision warnings. This shows that auditory in-vehicle displays are not only an effective method for information presentation in vehicles; they are the preferred modality when used in the instance of safety warning notifications.

Sounds used within auditory in-vehicle displays must be acceptable to users [16]. This must be achieved by using sounds that are neither unpleasant nor annoying. The meaningfulness of each sound is particularly important especially when an auditory in-vehicle display is used during emergency situations [13]. A good auditory in-vehicle display must therefore be easily understood by users and be able to be acted upon appropriately. Users must be able to know the meaning of each sound quickly and easily [21]. The manipulation of sonic parameters can be particularly useful when designing sounds to: ensure appropriate user responses, convey certain information pertaining to primary and secondary driving tasks, and improve driver attention [14]. For example, in order to provide a sense of urgency from sounds used for auditory in-vehicle displays, the repetition speed of a particular tone, the fundamental frequency used and its harmonicity all contribute to a sound's affect [13]. The loudness of a given tone is also important. It must be ensured that the sound can be heard over background noise, but not so loud as to induce hearing impairment or annoyance [11].

There is already much research into the use of sound as auditory icons and earcons for use within Advanced Driver Assistance Systems (ADAS) with varying degrees of success [4, 18]. Whilst some ADAS rely on the use of auditory feedback to present vehicular information to the driver, this is often achieved using either a mono or stereo speaker implementation [25]. Using only a mono/stereo configuration does not allow for information to be presented spatially. In this situation the location and direction of a sound cannot be utilised. Without providing a means to utilise both the location and direction of a particular sound, information is restricted to conveyance via sonic parameters such as frequency, duration, harmonicity, loudness and timbre. A report by the Federal High Administration of North America has suggested that the auditory channel is mostly suitable for simple messages and content that does not require the driver to engage in spatial perception [6]. It is important to note that the design guidelines stating this were published in 1998. This may have been the preferred case for a manually controlled vehicle in the 20th century. However, with an increasing trend to automate vehicle functions and systems, engaging in spatial auditory perception may no longer be unnecessary. Instead, it may produce substantial benefits in comparison to traditional mono/stereo speaker implementation. With the inclusion of spatialisation for information presentation, sound may become a powerful tool to keep the driver up to date on information related to an autonomous vehicle's intended actions.

Sound's ability to convey information quickly can be enhanced further by 3D spatialisation where particular sounds can be placed around the driver inside the vehicle.

For instance, to improve pedestrian awareness for drivers, one study by Ardavan and Chen [1] proposed the use of a 3D sound system to play back natural human sounds. Their use of sounds, such as the footsteps of a pedestrian walking, and the positioning and panning of these sounds through a loudspeaker set up positively increased driver awareness to situational events . The use of 3D audio spatialisation has also proved to have benefits when used for vehicular way-finding and situation awareness within a virtual driving simulator [8]. Previous studies have shown that it is important to ensure that the appropriate sound is used in order to convey the correct information regardless of position [26]. Doing so avoids confusion and ensures that the necessary information is delivered to the driver quickly without distraction [19].

PRELIMINARY FIELD STUDY

In order to collect information about the sounds given most attention to by drivers we first conducted a preliminary field study [2]. This study helped to understand which sounds participants felt provided more or less information whilst undertaking a common driving journey. The main goal was to acquire data that would help categorise vehicle sounds in terms of how much importance was given to them. It also provided an insight into user preferences regarding current vehicle sounds and any potential additions participants would like to hear. Moreover, we were able to determine whether any specific sonic attributes were perceived to be more or less important for information conveyance.

Procedure

The study was conducted with 8 participants (mean age range = 26-35, 2 female, 6 male). All participants held a valid driving license and had varying degrees of driving experience (mean range = 5 – 10 years). The study was undertaken within each of the participant's cars, which they either owned or had regular access to. They were asked to travel a commonly driven route for a minimum of 15 minutes. We ensured that the primary driving task was not impeded upon at any point whilst the study took place.

During this phase, the observer made a note of each different sound that occurred and how often it occurred. Participants were asked to raise a finger from the steering wheel if they were aware of the sound occurring. This was noted as the participant identifying a particular sound. The observer also made a note of each time a sound was noticed by the driver but not identified explicitly e.g. a horn being sounded and the driver looking around to see who or what was being beeped at but not raising their finger. The marking system deduced for the study enabled quick and easy notation of sound occurrences and ensured minimal driver distraction. In conjunction with the marking system, a pre-determined taxonomy of expected sounds created from the results of 2 pilot user evaluations was used.

The second stage of the study required drivers to mark on a 2-dimensional car diagram their preferred position for 6 specific sounds from our taxonomy. Participants were encouraged to place the sounds wherever they deemed appropriate in and around the vehicle. The sounds were; horn, indicator, ignition, clutch, braking and acceleration. Results suggested that participants ideally wanted sounds to be presented primarily in front and to the right hand side of the driving position (the study was conducted in the UK where vehicles drive on the left hand side of the road). Unusually participants expected some sounds that related to primary driving tasks to be presented at the source of where they interact with the sound trigger. For example, a number of participants marked the steering column as the location of the vehicle ignition sound. This finding hints towards the expectation of sounds occurring in already established positions. It also suggests that our participants were not aware that primary driving sounds could occur in positions other than those they are already familiar with.

CAR SOUND RECORDINGS

Vehicle Type	Sounds Characteristics
Volkswagen Polo 1.0 L (1999)	• Typical small capacity, economic engine sound • Somewhat loud • Older electronics (indicator, ignition etc.)
Volkswagen Golf 1.9 TDI (2007)	• Familiar diesel engine sound • Somewhat quiet • Modern electronics (indicator sound, ignition etc.) • Minimal mechanical sounds
Ford Escort Mk1 1.6 Petrol (1976)	• Powerful performance petrol engine • Very loud • Minimal electronics (no electric ignition, very quiet indicator sound) • Loud mechanical sounds

Table 2 - Sound characteristics of captured vehicle sounds

The field study helped determine the most commonly occurring driving sounds. These were: acceleration, braking, gear changing, clutch, indicator and ignition. Our next goal was to capture convincing and realistic versions of these sounds for use during the driving simulator study. We recorded each sound directly from its source while each car was stationary within a quiet indoor environment. This ensured our sounds were captured with minimal ambient reverberation, making them accurate in terms of harmonic content, duration, and amplitude. A local garage was used for the audio recordings providing access to multiple vehicles. It was deemed beneficial to record 3 different cars and acquire a set of convincing pre-recorded sounds[1]. 2

[1] Sounds captured from this task will be made available online as a data set of vehicle sounds (http://www.ittgroup.org/people/davidb)

Rode NTG-2 shotgun microphones with super-cardioid polar patterns were used to ensure no ambient noises were captured whilst recording. All sounds were recorded onto a laptop computer running Steinberg's Cubase Elements 7 multi-track recording software. There were several benefits to recording multiple vehicles. Primarily, each car had substantially different fundamental sound characteristics (see Table 2). For instance, the Ford featured a large, high-powered engine and provided a sportier sound in comparison to both the Volkswagens. For further details on this study see [2].

CAR SIMULATOR STUDY

The purpose of this study was to determine what effect the spatialisation of primary driving task sounds had on drivers of autonomous vehicles. This was achieved by presenting participants with 5 separate auditory presentation methods that featured in both autonomous and manual driving scenarios. The study investigated:

- User preferences towards our different auditory presentation methods to determine which is the most preferred;
- Whether spatialisation can enhance driver awareness of the intended actions of an autonomous vehicle;
- Whether auditory spatialisation assists in re-establishing a sense of control to drivers in autonomous vehicles.

In order to investigate these objectives, all participants undertook both autonomous and manual driving scenarios.

Participants

15 participants took part in the study, (11 male, 4 female), with a modal age range of 26 – 35. All had valid driving licenses held for a minimum of 1 year and either owned or had regular access to a car. They were all either postgraduate University students or in full-time employment. Their mean driving frequency range was 3 to 6 hours per week. 14 participants drove cars with manual transmission and 1 with automatic transmission.

Equipment

The experiment took place in a quiet University room, where participants sat on a padded chair in front of a desk with a 32-inch TV screen (Toshiba 32KVB). A laptop computer running the OpenDS driving simulator software was connected via HDMI cable. OpenDS is primarily designed with the intention to be used for research purposes [16] and is built on the JMonkeyEngine3[2]. Sound was delivered through a set of headphones (AKG K-451). Headphones were used as the 3D audio API produced a better effect in comparison to speakers. Participants controlled the vehicle during the manual scenarios via a Logitech Driving-Force GT gaming steering wheel[3]. Physical buttons on the steering wheel were mapped to the indicator, gear up/gear down and ignition on/off functions. OpenDS supports 3D audio by defining positional vector co-ordinates for mono sounds and setting the listener position as the camera location within the simulator itself. As OpenDS is built using JMonkeyEngine3, the 3D audio API used is OpenAL. This API provided adequate 3D audio representation for our study. For each auditory presentation, the positions of each sound were programmed within the OpenDS driving simulator and stored in separate .xml files.

Driving Task & Auditory Presentation Methods

Our study had 2 driving conditions and 5 auditory presentation methods, thus participants undertook 10 driving scenarios. The driving conditions were Level 0 automation (fully manual driving) and Level 4 automation (fully autonomous driving). During the Level 0 (manual) automation condition participants controlled OpenDS via the steering wheel and pedals. Participants were presented with the 'Paris' scenario that comes bundled with OpenDS. This scenario features a virtual environment consisting of inter-connected streets containing various traffic obstacles. Participants were asked to navigate their way around the scenario for a maximum of 2 minutes. 2 minutes per scenario was deemed appropriate so fatigue did not occur at any point during the study. Furthermore, it was felt that this amount of time would be satisfactory for participants to be aware of the associated task load per scenario. The Level 4 (autonomous) condition simulated an autonomous vehicle journey by presenting participants with pre-recorded video clips. These clips lasted 2 minutes and featured a series of manoeuvres again within the 'Paris' scenario. Participants were asked to sit and observe the journey, paying attention to the sounds, until the scenario completed.

Our 5 auditory presentation methods each contained sounds presented in differently spatialised manners. The 4 major sounds (acceleration, braking, indication and gear changing) relating to the primary driving task, identified from our preliminary study and captured during our sound recording stage, were used in each auditory presentation method. Auditory presentation method 1 (Standard Positions) featured sounds positioned traditionally as they would be in current manually driven vehicles. For instance, the indicator sound appeared to occur directly behind the steering wheel in a fixed location. Method 2 (User Inferred Positions) contained the positions of sounds obtained from our preliminary field study. This auditory presentation method featured the positions that were most frequently chosen by the participants. The majority of the positions only differed marginally in comparison to method 1.

[2] http://www.jmonkeyengine.org

[3] http://gaming.logitech.com/en-gb/product/driving-force-gt-gaming-wheel

Methods 3 (Static Spatialised Positions) and 4 (Dynamic Spatialised Positions) contained sounds presented spatially. During auditory presentation method 3 (Static Spatialised), the indicator sound was panned fully left or fully right depending on which direction the participant indicated. Auditory presentation method 4 (Dynamic Spatialised) differed from method 3 by changing the location of the acceleration sound as a participant depressed the accelerator pedal. As the intensity of the pedal press increased, the position of the acceleration sound moved towards the participant effectively increasing in intensity as the car gained speed. The order in which each participant received both the driving conditions and each auditory presentation method was randomised. Auditory presentation method 5 (No Sound Positions) presented no sounds.

Study Procedure

Procedure	Steps involved	Duration
Study Explanation/ Demographic Questionnaire	1.Study explained to participant 2.Demographic questionnaire completed	**5mins**
PHASE 1		
Simulator Practice	3.Participant shown driving simulator and undertakes practice scenario	**8 - 12mins**
PHASE 2		
Simulated Car Journey Driving	1.Participant undertakes each of the 10 simulated journeys 2.Between scenarios participant completes DALI/NASA-TLX & Likert Scale questionnaires	2 mins per scenario 3 mins per post scenario questionnaire = **30mins**
PHASE 3		
Post-Study Questionnaire	1. Post-evaluation questionnaire completed	**10mins**

Table 3 - Main procedures, steps involved and duration of each step for simulated study

Participants were first provided with an explanation of the study. Once willing to participate, a demographic questionnaire was filled out. A brief explanation of how to operate the simulator software was given. Participants were then encouraged to spend some time becoming familiarised with the driving simulator. After participants signalled they were confident with control of the simulated vehicle, the study commenced. A description of the steps involved in the procedure is shown (Table 3).

Data Gathering Methods

Twelve 5-point Likert scale questions were given between scenarios. These provided quantitative data for specific questions relating to our objectives and focused on the positioning of the sounds, level of control felt by the participant and the audio itself e.g. pitch, timbre and volume. A NASA-TLX questionnaire was also used, as it is an accepted means of documenting participant workload in relation to a specific task. The DALI [20] questionnaire, based on the NASA-TLX but adapted specifically to evaluate driving task workload, was also used. All questionnaires were filled out by the participants after each task. It was deemed useful in order to determine the effect different auditory presentation methods had on driver workload. Furthermore, it allowed specific factors to be evaluated such as: *Auditory Demand*, *Visual Demand* and *Situational Stress*.

RESULTS

In this section we present the findings from our 5-point Likert scale questionnaire, Driver Activity Load Index (DALI) and NASA-TLX questionnaires. All responses were analysed using 2-way repeated measure ANOVAs, with driving scenario (2 levels) and auditory presentation method (5 levels) as factors.

Likert-Scale Analysis

Participants were asked whether the auditory feedback during each driving scenario enhanced their awareness of the vehicle's actions (Q1 Table 4). When comparing the autonomous and manual driving scenarios, no significant difference was found. However, comparisons between auditory presentation methods found a significant difference ($F(1.95,27.36) = 80.84$ $p<0.001$) with Greenhouse-Geisser adjustment. A pairwise comparison using a Bonferroni adjusted alpha showed all auditory presentation methods were significantly different to the no sound auditory presentation method ($p<0.001$). Participants were also asked whether the position of sounds presented during each scenario alerted them to the intended actions of the vehicle (Q2 Table 4). There was a significant difference for the auditory presentation methods ($F(4,56) = 30.50$ $p<0.001$). Pairwise comparisons with a Bonferroni adjusted alpha showed that responses for the static spatialised auditory presentation method was significantly different when compared to the standard, user inferred and no sound presentation methods ($p<0.001$). Again, pairwise comparisons between all auditory presentation methods and the no sound presentation method proved to be significant ($p<0.001$). This suggests that it is imperative to provide some form of auditory feedback during both manual and autonomous driving scenarios and that some thought needs to be given to what the autonomous auditory feedback should be. We wanted to know if the sounds alerted the participants to the intended action of the vehicle and there was a difference when comparing the driving scenarios to the auditory presentation methods ($F(4,56) = 2.904$ $p=0.03$). We asked if participants felt the auditory feedback presented during each scenario was a distraction to the primary driving task (Q3 Table 4). We found no significant difference between manual and autonomous driving scenarios.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Manual Condition (All Sound Presentation Methods**)**	3.23, *SD*=1.43	3.04, *SD*=1.35	2.09, *SD*=1.10	3.47, *SD*=1.22	3.20 *SD*, *SD*=1.27	3.23, *SD*=1.26	3.27, *SD*=1.26	3.04, *SD*=1.27	2.87, *SD*=1.04	3.51, *SD*=1.37	2.87(4), *SD*=1.28	3.07(4), *SD*=1.36
Autonomous Condition (All Sound Presentation Methods**)**	3.25, *SD*=1.42	3.01, *SD*=1.46	2.20, *SD*=1.26	1.91, *SD*=1.18	3.00, *SD*=1.35	3.19, *SD*=1.26	3.12, *SD*=1.17	2.85, *SD*=1.26	2.76, *SD*=0.98			
Standard Sound Positions (Both Manual & Autonomous Driving Conditions**)**	3.43, *SD*=0.97	3.00, *SD*=1.14	1.90, *SD*=0.71	3.00, *SD*=1.51	3.53, *SD*=1.04	3.70, *SD*=0.75	3.80, *SD*=0.66	3.47, *SD*=0.86	3.27, *SD*=0.52	3.87(4), *SD*=0.74	2.87(2), *SD*=0.99	2.73(4), *SD*=1.33
User Inferred Sound Positions (Both Manual & Autonomous Driving Conditions**)**	3.30, *SD*=0.99	2.83, *SD*=0.99	1.97, *SD*=0.72	2.80, *SD*=1.52	3.60, *SD*=0.93	3.47, *SD*=0.82	3.43, *SD*=1.04	3.17, *SD*=1.12	3.17, *SD*=0.46	3.87(4), *SD*=0.74	2.93(4), *SD*=1.03	3.07(4), *SD*=1.03
Static Spatialised Sound Positions (Both Manual & Autonomous Driving Conditions**)**	4.33, *SD*=0.92	4.47, *SD*=0.90	1.77, *SD*=1.10	3.00, *SD*=1.31	3.63, *SD*=0.96	3.90, *SD*=0.84	3.80, *SD*=0.66	3.53, *SD*=0.97	3.23, *SD*=0.43	4.33(5), *SD*=0.82	3.80(4), *SD*=0.96	4.20(4), *SD*=0.68
Dynamic Spatialised Sound Positions (Both Manual & Autonomous Driving Conditions**)**	4.13, *SD*=0.57	3.37, *SD*=0.96	1.80, *SD*=0.71	3.03, *SD*=1.47	3.57, *SD*=0.90	3.70, *SD*=0.88	3.60, *SD*=0.72	3.40, *SD*=0.89	3.40, *SD*=0.56	4.20(4), *SD*=0.41	3.60(4), *SD*=0.83	3.73(4), *SD*=0.96
No Sounds (Both Manual & Autonomous Driving Conditions**)**	1.00, *SD*=0.00	1.47, *SD*=1.11	3.30, *SD*=1.64	1.60, *SD*=0.67	1.17, *SD*=0.53	1.27, *SD*=0.64	1.33, *SD*=0.71	1.17, *SD*=0.53	1.00, *SD*=0.00	1.27(1), *SD*=1.03	1.13(1), *SD*=0.52	1.60(1), *SD*=1.12

Table 4 - Mean and standard deviations for Likert scale results for questions 1 - 12

	Effort of Attention	**Visual Demand**	**Auditory Demand**	**Temporal Demand**	**Interference**	**Situational Stress**	**TOTAL**
Manual Condition (All Sound Presentation Methods**)**	2.88, *SD*=1.28	2.92, *SD*=1.12	2.52, *SD*=1.29	2.41, *SD*=1.15	3.15, *SD*=1.32	2.83, *SD*=1.44	16.71, *SD*=5.15
Autonomous Condition (All Sound Presentation Methods**)**	1.19, *SD*=1.00	1.47, *SD*=1.18	1.61, *SD*=1.32	0.76, *SD*=0.91	1.23, *SD*=1.42	1.92, *SD* =1.39	8.17, *SD*=5.29
Standard Sound Positions (Both Manual & Autonomous Driving Conditions**)**	1.93, *SD*=1.46	2.40, *SD*=1.38	2.20, *SD*=1.16	1.70, *SD*=1.39	2.07, *SD*=1.74	1.93, *SD* =1.36	12.23, *SD*=6.98
User Inferred Sound Positions (Both Manual & Autonomous Driving Conditions**)**	2.03, *SD*=1.52	2.03, *SD*=1.30	2.03, *SD*=1.16	1.53, *SD*=1.36	2.27, *SD*=1.68	2.03, *SD* =1.43	11.93, *SD*=6.57
Static Spatialised Sound Positions (Both Manual & Autonomous Driving Conditions**)**	1.73, *SD*=1.28	1.77, *SD*=1.30	2.00, *SD*=1.34	1.50, *SD*=1.14	2.03, *SD*=1.65	2.10, *SD* =1.16	11.13, *SD*=6.20
Dynamic Spatialised Sound Positions (Both Manual & Autonomous Driving Conditions**)**	1.90, *SD*=1.16	1.93, *SD*=1.28	2.03, *SD*=1.30	1.37, *SD*=1.19	2.10, *SD*=1.69	2.20, *SD* =1.35	11.53, *SD*=6.17
No Sounds (Both Manual & Autonomous Driving Conditions**)**	2.57, *SD*=1.61	2.83, *SD*=1.34	2.07, *SD*=1.89	1.83, *SD*=1.56	2.47, *SD*=1.68	3.60, *SD* =1.50	15.37, *SD*=7.28

Table 5 - Mean & standard deviations of DALI factors for driving scenarios & auditory presentation methods

	Physical Demand	**Mental Demand**	**Temporal Demand**	**Performance**	**Effort**	**Frustration**	**TOTAL**
Manual Condition (All Sound Presentation Methods**)**	4.28, *SD*=4.31	3.95, *SD*=4.17	3.33, *SD*=4.31	2.83, *SD*=2.37	3.91, *SD*=3.93	3.75, *SD*=3.87	22.04, *SD*=21.72
Autonomous Condition (All Sound Presentation Methods**)**	1.52, *SD*=1.73	2.20, *SD*=3.21	1.65, *SD*=1.33	1.11, *SD*=2.17	1.32, *SD*=1.48	2.68, *SD*=3.12	10.48, *SD*=9.85
Standard Sound Positions (Both Manual & Autonomous Driving Conditions**)**	2.83, *SD*=3.36	2.77, *SD*=2.96	2.60, *SD*=3.07	2.10, *SD*=2.58	2.50, *SD*=3.50	2.43, *SD*=2.53	15.23, *SD*=17.21
User Inferred Sound Positions (Both Manual & Autonomous Driving Conditions**)**	3.07, *SD*=3.98	3.20, *SD*=4.04	2.50, *SD*=3.45	2.60, *SD*=3.98	2.67, *SD*=3.30	2.97, *SD*=3.96	17.00, *SD*=20.51
Static Spatialised Sound Positions (Both Manual & Autonomous Driving Conditions**)**	2.57, *SD*=3.48	2.60, *SD*=3.67	2.43, *SD*=3.17	1.70, *SD* =1.53	2.53, *SD*=3.20	2.83, *SD*=2.68	14.67, *SD*=16.58
Dynamic Spatialised Sound Positions (Both Manual & Autonomous Driving Conditions**)**	2.57, *SD*=3.37	3.00, *SD*=4.06	2.50, *SD*=3.25	1.47, *SD*=1.11	2.50, *SD*=2.70	3.20, *SD*=3.78	15.23, *SD*=16.39
No Sounds (Both Manual & Autonomous Driving Conditions**)**	3.47, *SD*=3.68	3.80, *SD*=4.34	2.43, *SD*=3.68	1.97, *SD*=1.81	2.87, *SD*=3.57	4.63, *SD*=4.25	19.17, *SD*=18.71

Table 6 - Mean and standard deviations of NASA-TLX factors for driving scenarios & auditory presentation methods

The use of different auditory presentation methods during the scenarios showed differences ($F(1.53,21.39) = 9.69$ $p=0.002$) with Greenhouse-Geisser adjustment. In particular, after running a pairwise comparison with a Bonferroni adjusted alpha, it was found that the no sound presentation method was a distraction in comparison to the standard auditory presentation method ($p=0.003$). This again highlights the need for some form of auditory presentation method so that there is no significant distraction caused during either manual driving or autonomous driving scenarios.

Participants were asked to state whether they felt in control of the vehicle at any point during each scenario (Q4 Table 4). Comparing the autonomous and manual driving scenarios shows participants felt more in control during the manual driving scenarios in comparison to the autonomous driving scenarios ($F(1,14)=80.66$ $p<0.001$). The auditory presentation methods show a significant difference between scenarios ($F(4,56) = 14.004$ $p<0.001$). Pairwise comparison with a Bonferroni adjusted alpha again showed significant differences between no sound and all other scenarios (standard sound ($p=0.001$), user inferred ($p=0.002$), static spatialised ($p<0.001$), and dynamic spatialised ($p=0.002$)).
We asked a number of other questions during the Likert-scale stage of our evaluation. These questions asked participants whether the sound parameters: Pitch (Q5), Repetition (Q6), Duration (Q7), Timbre (Q8) and Volume (Q9), respectively, played a role in enhancing their awareness to the intended actions of the vehicle. Results show significant differences between driving scenarios (manual & autonomous) for *Pitch* ($F(1,14)=8.007$ $p=0.013$) and *Timbre* ($F(1,14)=5.237$ $p=0.038$). This finding raises the question why these particular sonic attributes were more significantly different in comparison to *Repetition, Duration,* & *Volume* during the manual driving scenarios. All of the auditory presentation methods were significant different to the no sound presentation method. This was expected as none of these sonic parameters were present during this auditory presentation method ($p<0.001$ for all). Three final questions were asked after manual driving scenarios only. These questions related to a participant's own actions and the impact the different auditory presentation methods had. All auditory presentation methods containing sound were significantly different when compared in a pairwise manner to the no sound presentation method ($p<0.001$ for all).

DALI & NASA-TLX Workload
A summary of feedback for the DALI questionnaire is shown in Table 5. DALI total workload was significantly lower during the autonomous driving scenarios in comparison to the manual driving scenarios ($F(1,14)=34.72$ $p<0.001$). When comparing all auditory presentation methods containing sounds vs. the no sound condition there was a significant difference, with a Greenhouse-Geisser adjustment ($F(1.89,26.01) = 5.76$ $p=0.01$). However, using a Bonferroni adjusted alpha, pairwise comparisons between each auditory presentation method found no significant differences. In keeping with the results from the DALI questionnaire, the NASA-TLX results showed workload was significantly different between manual and autonomous driving scenarios ($F(1,14)=6.21$ $p=0.026$) with a Greenhouse-Geisser adjustment. The NASA-TLX values for each auditory presentation method did not yield any significant differences. A summary of feedback for the NASA-TLX questionnaire is shown in Table 6.

DISCUSSION
Our first objective was to measure user preferences towards our different auditory presentation methods to determine which is the most preferred. We did not find any significant differences for any particular auditory presentation method in terms of workload comparison. However, participant feedback suggests that overall users scored the static spatialised audio presentation method lowest for *Total Workload*, *Auditory Demand*, *Effort of Attention*, *Visual Demand* and *Interference*. This is in contrast to the driving scenarios that contained the no sound presentation method, where mean overall workload was scored higher than all other auditory presentation methods. While no significant differences were found, an observation can be made that some form of auditory feedback should be presented to participants when undertaking simulated autonomous driving to ensure workload is not increased. Results from the Likert scale questions clearly show some benefit that auditory feedback has in comparison to no auditory feedback. In particular, users felt that all of the auditory presentation methods enhanced their awareness of the vehicle's actions. Our second objective was to determine whether spatialisation could enhance driver awareness of the intended actions of an autonomous vehicle. The spatialised auditory presentation methods yielded significantly more positive responses in comparison to the other auditory presentation methods for alerting participants to the intended actions of the autonomous vehicle. Our findings also suggest that auditory feedback, in comparison to no auditory feedback, is a necessity for enhancing driver awareness to the intended actions of an autonomous vehicle. Participants were asked whether any of the auditory presentation methods were felt to be a distraction during any of the scenarios. Only the no sound presentation method was found to be a distraction. This suggests that the design guidelines laid out by Campbell et al [6] may need revisiting regarding the use of spatialisation within vehicles. More pertinently, spatialisation was not found to cause a distraction during any of the simulated autonomous driving scenarios. This gives promise to the use of a spatialised auditory in vehicle display that enhances driver awareness without causing any unnecessary distraction in comparison to standard auditory presentation methods.

Our final objective was to determine whether auditory spatialisation assists in re-establishing a sense of control to drivers in autonomous vehicles. Whilst it was clear that users felt more in control during the manual driving scenarios, there were no results that indicate conclusively that auditory spatialisation improved their sense of control. However, it is important to note that having no sounds presented decreased participants' sense of control significantly, highlighting the need to have some form of auditory feedback in future car design.

Our analysis has shown that overall workload (as measured using a NASA-TLX and DALI questionnaires) is lower when participants travel in a simulated autonomous vehicle in comparison to manual driving scenarios. However when looking at individual workload parameters, we found that whilst users undertook the manual driving scenarios, their visual demand was higher in comparison to their auditory demand (as measured by DALI). The opposite was found to be the case when participants were undertaking the autonomous driving scenarios. While there was no significance found for these findings, there is positive reason to repeat this study with a larger user group. In particular, the inclusion of European drivers may produce interesting results.

CONCLUSION & FUTURE WORK

In this paper we explored the use of auditory spatialisation within a simulated autonomous vehicle to answer three objectives. Our first objective was to determine user preferences towards our different auditory presentation methods to determine which is the most preferred. Our findings do not directly show whether there is a preferred auditory presentation method. However, the static spatialisation presentation method scored lowest in terms of total workload for both DALI and NASA-TLX questionnaires. Furthermore participants scored the spatialised auditory presentation method higher in comparison to all other presentation methods for enhancing awareness to the intended actions of the vehicles in our study. While there was no significant difference between audio presentation methods for enhancing there was a trend towards spatialisation as being the most preferred auditory presentation method. Our second objective was to determine whether auditory spatialisation could enhance driver awareness of the intended actions of an autonomous vehicle. We found that there were significant differences between all auditory presentation methods containing sounds vs. the no sound presentation method, with participants having a more positive response to the presentation methods contain sound. We also found that the spatialised auditory presentation was significantly different from all the other auditory presentation methods for alerting drivers to the intended actions of the autonomous vehicle, with spatilisation having a positive effect. Moreover, only when participants were presented with the no sound auditory presentation method were they significantly distracted from the primary driving task.

The final goal in this study was to understand whether auditory spatialisation could assist in re-establishing a sense of control to drivers in autonomous vehicles. Our findings indicate that users feel less in control when no sound is presented. Our future work will examine this research direction in more detail. It would be beneficial to repeat this study with European drivers, as only UK drivers were used who are required to drive on the left hand side of the road.

Another outcome from this study is that for simulated autonomous driving the workload is significantly lower in comparison to simulated manual driving. While this was the case for all of our auditory presentation methods, when drivers were presented with no sound feedback, the workload was comparatively higher. In relation to Kraus et al. [12], when attempting to ensure that driver awareness of autonomous vehicle actions is maintained, importance must be placed on auditory feedback.

An interesting research direction highlighted by the findings from this work indicates that investigations into what effect different sonic parameters have in enhancing driver awareness is required to enable the design of auditory displays for autonomous vehicles. For example, we found that *Pitch* and *Timbre* play a role in enhancing driver awareness during the manual driving scenarios. It is important to ascertain why these particular parameters seemed to have more effect than *Repetition*, *Duration*, and *Volume*. We are therefore planning a study that will investigate what effect manipulating these parameters has on driver awareness as we believe, given the results from this study, that understanding the combination of spatialisation and sound parameters will ultimately re-establish a sense of control to drivers in autonomous vehicles.

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