Understanding and Improving Methods for Exterior Sound Quality Evaluation of Hybrid and Electric Vehicles

By

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Declaration

The author declares that all the work contained within this thesis is her own work and has not been used previously.

All the research was undertaken independently at WMG, University of Warwick. All preparation, conduct, analysis and interpretation of the work was carried out by the author. No other data sources were used.

This thesis has not been submitted for a degree at any other university.

This thesis is presented in accordance with the regulations of the University of Warwick.

List of Publications

Parts of this research work have been published in the following:

[1] S. Singh, S. R. Payne, J. B. Mackrill, and P. A. Jennings, (2015). “Do experiments in the virtual world effectively predict how pedestrians evaluate electric vehicle sounds in the real world?”, Transportation Research Part F: Traffic Psychology and Behaviour, vol. 35, pp. 119–131. Doi: 10.1016/j.trf.2015.10.012

[2] S. Singh, S. R. Payne, and P. A. Jennings, (2014). “Toward a Methodology for Assessing Electric Vehicle Exterior Sounds”, IEEE T INTELL TRANSP, vol. 15, no. 4, pp. 1790-1800. Doi: 10.1109/TITS.2014.2327062

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Abstract

Electric and Hybrid Electric Vehicles [(H)EVs] are harder for pedestrians to hear when moving at speeds below 20 kph. Laws require (H)EVs to emit additional exterior sounds to alert pedestrians of the vehicles' approach to prevent potential collisions. These sounds will also influence pedestrians' impression of the vehicle brand. Current methods for evaluating (H)EV exterior sounds focus on "pedestrians' safety" but overlook its influence on "vehicle brand", and do not balance experimental control, correct context along with external and ecological validity.

This research addresses the question: "How should (H)EV exterior sounds be evaluated?" The research proposes an experimental methodology for evaluating (H)EV exterior sounds that assesses pedestrians' safety and influence on the vehicle brand by measuring a listener's detection rate and sound quality evaluation of the (H)EV in a Virtual Environment (VE). This methodology was tested, improved and validated through three experimental studies based on their findings.

Study 1 examined the fidelity of the VE setup used for experiments. The VE was immersive with sufficient degree of involvement/control, naturalness, resolution, and interface quality. It also explored a new interactive way of evaluating (H)EV sounds where participants freely navigate the VE and interact with vehicles more naturally. This interactivity increased the experiments' ecological validity but reduced reliability and quadrupled the experiment duration compared to using a predefined scenario (non-interactive mode). Thus, a predefined scenario is preferred.

Study 2 tested the non-interactive mode of the proposed methodology. Manipulating the target vehicle's manoeuvre by varying factors, namely the vehicle's "arrival time", "approach direction" and "distance of travel", across the experiment conditions increased ecological validity. This allowed participants to think, respond and pay similar attention as a real world pedestrian. These factors are neglected by existing methodologies, but were found to affect the participants' detection rate and impression of the vehicle brand. Participants detected the vehicle more than once due to confusion with real world ambient sounds. In the real world, pedestrians continuously detect a vehicle in presence of non-vehicular ambient sounds. Therefore, recommendations to improve the representation of the real-world processes in the vehicle detection during listening experiments include an option to re-detect a vehicle and subjective evaluation of 'detectability' of the vehicle sounds.

The improved methodology adds 'detectability' and 'recognisability' of (H)EV sounds as measures and (H)EV's arrival time as an independent variable. External validity of VEs is a highly debated yet unanswered topic. Study 3 tested external validity of the improved methodology. The methodology accurately predicted participants' real world evaluations of the detectability of (H)EV sounds, ranked order of the recognisability of (H)EV sounds and their impressions about the vehicle brand. The vehicle's arrival time affected participants' detection rate and was reaffirmed as a key element in the methodologies for vehicle sounds' detection.

The final methodological guidelines can help transportation researchers, automotive engineers and legislators determine how pedestrians will respond to the new (H)EV sounds.

Abbreviations

Abbreviation	Full form as used within this thesis
(H)EV	Fully Electric Vehicles and Hybrid Electric Vehicles capable of running in electric mode
≈	approximately
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
cd/m^2	Candela per square metre
dB(A)	A-weighted Decibel Level
ESS	Exterior Sound Simulator
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
kph	kilometres per hour
m	metre(s)
mph	miles per hour
NHTSA	National Highway Traffic Safety Administration, USA
NVH	Noise, Vibration and Harshness
s	second(s)
SPL	Sound Pressure Level
UNECE	United Nations Economic Commission for Europe
VE	Virtual Environment
VR	Virtual Reality

Chapter 1: Introduction

1.1. Introduction

This chapter introduces the challenges of legislation-driven additional sounds for Electric Vehicles and Hybrid Electric Vehicles ((H)EVs). It further summarises the gaps in the current methods of automotive exterior sound quality evaluations. This helps establish the motivation for this research, the research question and objectives. A description of the thesis structure provides a close to the chapter.

1.2. Research Background

1.2.1. Growth of (H)EVs

Although the earliest (H)EVs date back to the mid-19th century [1]–[3], their production and sale then was very limited. It is since the 1970s that the energy crises and rise in petroleum fuel prices, have raised the interests in (H)EVs [1]–[3]. This has led to increase in the production and sale of (H)EVs, especially in the last two decades [1]–[3]. The recent advancements in HEV technology such as plug-in HEVs and vehicle-to-grid plug-in HEVs [1], [4] allows them to generate energy from sources other than petroleum fuels unlike the Internal Combustion Engine Vehicles (ICEVs). Furthermore, Electric Vehicle (EV) technology has improved due to the development of advanced batteries, ultracapacitors, and fuel cell technology [1], [2],

[5]. These developments provide higher energy efficiency, rapid refuelling, durability and reliability than their traditional counterparts [5]. The advanced electric motor drives improve range and lower the cost of EVs [2], [5]. Moreover, compared to current ICEVs these (H)EVs require less maintenance, produce less emission and have improved acceleration and higher fuel economy/ energy efficiency [1], [4]–[6].

As of October 2014, 604,000 plug-in (H)EVs have been sold worldwide, a growth of 20% in four months [7]. Their major market are the United States (260,000 units) and Japan (95,000 units) [7]. (H)EVs have maximum market share in Netherlands and Norway where they constitute 5% and 15% of the total vehicle fleet respectively [8]. *"[Ultimately] with the ever more stringent constraints on energy resources and environmental concerns, HEVs will attract more interest from the automotive industry and the consumer"* [1:718].

1.2.2. Why do (H)EVs need additional sounds?

(H)EVs are quieter at low speeds compared to ICEVs. Research suggests that the Sound Pressure Level (SPL) of an EV or an HEV in EV mode can be 20 dB(A) lower than an ICEV of a similar make and weight when idling [9], [10]. This SPL difference is very large considering the fact that a human ear can distinguish up to 3 dB(A) SPL difference, here 3dB(A) being Just Noticeable Difference (JND) [11]. The SPL differences between (H)EVs and ICEVs decrease with vehicle speed becoming insignificant (less than 3 dB(A),) at speeds above 20 kph [9], [10]. Since the early 2000s the public, and in particular advocacy groups for the blind and visually impaired such as the National Federation of the Blind (NFB) have been raising concerns about the lack of sound in (H)EVs [10], [12]–[17]. They advocate that the relative 'quietness' of these vehicles often renders pedestrians and cyclists unable to detect (H)EVs in time to avoid a potential collision [10], [12]–[17]. Thus, the relative 'quietness' (H)EVs may be a threat to the safety of pedestrians and cyclists.

Different solutions have been proposed to resolve this issue as summarised below:

I. Environmental regulations to reduce vehicles' SPL upper limits and the overall urban ambient sounds so that "quieter" vehicles become more audible [10], [18], [19].

II. Infrastructure-based solutions such as auditory pedestrian signals that produce acoustic warnings to inform pedestrians of a safe time to cross at traffic signals [10]. Additionally, pedestrian detection systems can produce acoustic and visual warnings whenever pedestrians approach crossroads and junctions [10].

III. Orientation and mobility training for blind pedestrians and guide dogs, and better training of drivers [10], [18], [19].

IV. Pedestrian-held devices to generate audio/tactile signals upon a vehicle's approach or pedestrian-vehicle proximity based devices that alert drivers or induce automatic braking upon pedestrian detection [10], [18], [19].

V. Emanation of additional sounds using devices fitted to the (H)EVs [10], [20]–[23].

The environmental regulations will take a long time for full implementation given the numerous and often unmanageable urban ambient sound sources e.g. construction, industry, recreational, animal and nature [10]. The infrastructure-based solutions require high cost and are also less effective as they only cover signalised crossroads and junctions which constitute a small portion of the possible danger points of pedestrian-vehicle interaction [10]. Training programmes already exist for visually impaired and guide dogs [10], so some researchers and advocacy groups for the visually impaired consider that these measures may not have the potential for further safety gain [10]. Moreover, these measures are limited to the visually impaired using guide dogs [10]. The pedestrian-vehicle proximity based devices are currently difficult to implement as they would increase vehicle costs and most pedestrians are not in favour of carrying a detection device every time they step outside the house [10].

Currently, the emanation of additional sounds using devices fitted to the (H)EVs is considered as the most feasible solution to the problem of these ‘quiet’ vehicles [10], [20]–[23]. From here on, the phrase **“(H)EV sounds”** will refer to these additional sounds emanated by the (H)EVs using any vehicle-based sound emitting device. Prominent legislation for (H)EV sounds is Japanese government’s Approaching Vehicle Audible System (AVAS) guidelines [21], US government’s Federal Motor Vehicle Safety Standard (FMVSS) [24] and Global Technical Regulation (GTR) by the United Nations Economic Commission for Europe (UNECE) [25]. Research shows that (H)EVs’ inherent sound increases with increasing speed as the tire-road interaction sound starts dominating, thus additional sound is only required below a certain speed [9], [10], [20], [21], [24], [25]. Thus, these standards stipulate that (H)EVs should emit sounds continuously until they attain a speed between 20 kph to 41 kph and at idle and reverse to alert pedestrians, cyclists and other road users of the vehicles’ approach to prevent potential collisions [21], [23]–[25].

1.2.3. Challenges in evaluating future (H)EV sounds

A vehicle's sound reinforces the vehicle brand. It plays a key role in identifying and distinguishing the brand of the vehicle [26], [27]. This could be elicited with examples such as Jaguar cars or Harley Davidson motorcycles where sound is a key aspect in identifying, recognising and distinguishing the vehicle brand from other competitor vehicles [26], [27]. Therefore, enhancing and tailoring the vehicle sound quality is a key technique for vehicle branding [26]–[30]. In case of (H)EV exterior sounds, a pedestrian hearing the exterior sound could evaluate the vehicle in terms of simply wanting to hear the vehicle pass-by, or as a potential consumer who may want to purchase the vehicle. Therefore, vehicle manufacturers want the (H)EV sounds to promote positive impressions of the vehicle brand [26]. At the same time, it is necessary to preserve the soundscape benefits of the current 'quietness' of these vehicles. The (H)EV sounds must not add to the existing traffic noise related annoyance. In fact, there is an opportunity to reduce traffic noise through (H)EV sounds that may have an overall neutral or positive effect on soundscapes. Safety, brand, and soundscapes are the competing criteria for the evaluation of (H)EV exterior sounds.

Currently, (H)EV exterior sounds' evaluation methods assess pedestrians' safety via detection tests [10], [31]–[35]. However, these methods do not assess these (H)EV exterior sounds to check their influence on the vehicle brand. Automotive engineers and transportation researchers need a rigorous methodology for evaluating potential (H)EV sounds to ensure they are detectable whilst also promoting positive impressions of the vehicle brand. In the context of this research, the term "**evaluation**" of (H)EV exterior sound quality or simply "**evaluation**" of

(H)EV exterior sounds will refer to the detection as well as the perceptual evaluation of subjective sound quality attributes of the (H)EV.

Existing automotive exterior sound quality evaluations are usually conducted on-road or inside a laboratory. When evaluations are conducted on-road, pedestrians evaluate (H)EV sounds while receiving visual and auditory stimuli of the urban traffic scenarios [9], [31], [32], [36], [37]; sometimes with additional vehicles, and other sound sources [31], [36]. This is similar to the stimuli pedestrians receive while evaluating vehicle sounds in the real world. Therefore, on-road evaluation methods provide an appropriate context for evaluating vehicle sounds. However, these methods do not provide control on external factors, such as, changes in the background sounds, visuals, traffic, and weather [31], [36]. Laboratory evaluation methods provide better experimental control [10], [33], [34], [37], [38]. However, existing laboratory evaluation methods use a single stimulus (target vehicle's sound); so they lack the appropriate context. Moreover, existing methodologies have not been validated ecologically or externally. Figure 1.1 summarises the gaps in the current methodologies. Hence, there is a need for a standard methodology for "**evaluating**" (H)EV exterior sounds that bridges these gaps by balancing experimental control with an appropriate context and external and ecological validity.

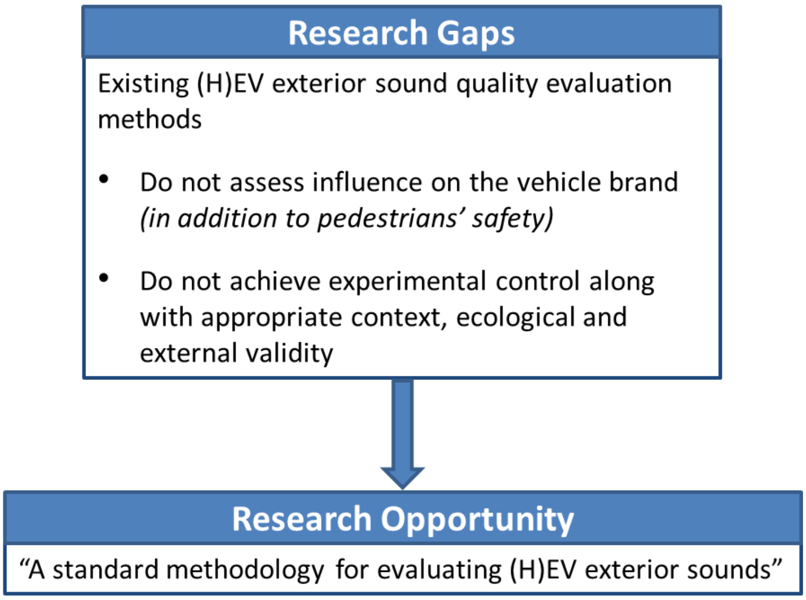


Figure 1.1 Gaps in (H)EV exterior sound quality evaluation methods

1.3. Research Scope

1.3.1. Research question and objectives

This research aimed at understanding and improving the methods for evaluating (H)EV exterior sound quality from the perspective of its use by the automotive industry, sound quality experts, transportation researchers and policy makers. Therefore, the research focused on the criteria of safety and brand for evaluating (H)EV sounds. The research question under investigation was:

"How should (H)EV exterior sounds be evaluated?"

To answer the research question in a rigorous and systematic manner the following objectives were set:

I. To formulate an experimental methodology for evaluating (H)EV exterior sounds that includes the criteria of pedestrians' safety and vehicle brand and provides an appropriate evaluation context and experimental control.

II. To examine the fidelity of the experimental setup and the quality of user experience.

III. To assess reliability, control and ecological validity of the experimental methodology when it is applied to a pedestrian interacting with an (H)EV in a traffic scenario critical to pedestrians' safety.

IV. To externally validate the methodology by determining if it accurately predicts pedestrians' evaluation of (H)EV sounds in the real-world.

V. To compare aspects such as the duration, implementation, reliability and control of the methodology to the real-world (on-road) evaluation approach

VI. To produce methodological guidelines for evaluating (H)EV exterior sounds.

1.3.2. Research impact

The research aimed at proposing an evaluation methodology that has benefits over existing automotive sound quality approaches by achieving an appropriate context, experimental control, ecological and external validity. The research output is a set of methodological guidelines that can be applied to the automotive industry in their Noise, Vibration, and Harshness (NVH) process of vehicle design. Moreover, the knowledge gained about how pedestrians' detect and evaluate (H)EV sounds would benefit policy makers of these (H)EV sounds, manufacturers and brand managers, and the general public, especially pedestrians.

1.4. Thesis Structure

The thesis consists of eight chapters that follow a systematic approach to address every research objective. Figure 1.2 shows the structure of the thesis and links the research objectives with the thesis chapters.

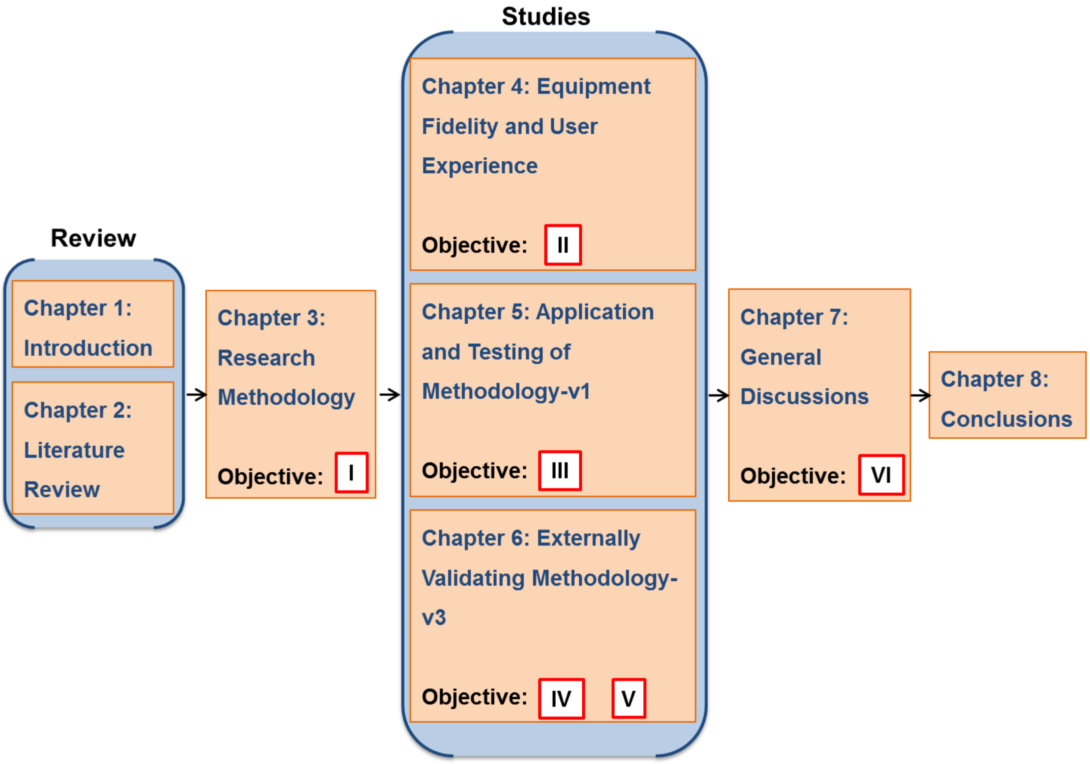


Figure 1.2 The thesis structure

Chapter 2 reviews the literature primarily to identify the major challenges and requirements of (H)EV sounds. The existing automotive sound quality evaluation methods are also reviewed in the context of experimental design and cognitive psychology. Gaps are identified in the current methods. Chapter 3 describes the overall research framework and process. It proposes an initial methodology, "**methodology-v1**" (version 1 of the methodology), for evaluating (H)EV exterior sounds. Further, it describes the research instrument and laboratory used for the evaluation experiments conducted as part of this research.

Chapters 4, 5 and 6 describe the experimental studies that test, validate and improve methodology-v1 through an iterative process. Chapter 4 contains exploratory study 1 that examines the fidelity of the experimental setup and the quality of user experiences during evaluation. The feasibility of evaluating (H)EV exterior sounds in an interactive way is also assessed. Chapter 5 presents study 2 that applies methodology-v1 to assess its reliability, control and ecological validity. This helps gain a better insight on how pedestrians detect and evaluate vehicles. Based on the learning from previous chapter, Chapter 6 proposes an improved version (version 2) of the methodology, namely, "**methodology-v2**". Further, it describes study 3 that compares methodology-v2 with a real-world evaluation method. Thus, it tests external validity of methodology-v2 by examining the generalizability of the results to a real-world environment.

Chapter 7 discusses the results from chapters 4, 5 and 6 together in the context of the literature, while highlighting the knowledge contribution and the potential research impact. Chapter 7 also presents the final methodological guidelines for evaluating (H)EV exterior sounds, namely "**methodology-v3**" (improved version 3 of the methodology). The final guidelines are a result of the iterative process of testing, validating and improving methodology-v1 through chapters 4 to 6. The thesis ends with a summary of key conclusions in Chapter 8.

Chapter 2: Literature Review

2.1. Introduction

The latest legislation mandates that (H)EVs will start emitting new sounds on a mass scale by 2018 [24], [39]. These sounds will be implemented primarily to ensure that (H)EVs are ‘audible enough’ for pedestrians’ safety. However, the manufacturers are just as interested in how these sounds will influence the perception of the vehicle brand. “Evaluation of these (H)EV sounds”, henceforth, is a major challenge to the automotive sound quality experts with its end-users being the automotive industry, policy makers, and most importantly the general public that will have to hear these sounds on a daily basis.

This chapter reviews the literature and the legislation to identify the major challenges and requirements of the (H)EV sounds. Following this, the existing methods for evaluating automotive sounds are critically reviewed in the context of experimental design and cognitive psychology. This helps identify gaps in the existing methods for automotive exterior sound quality evaluation and in current knowledge related to pedestrians’ evaluation of automotive sounds. The research gaps lead to the formulation of the research question and specific objectives that help address the research question.

2.2. Threat to Pedestrian's Safety due to Quietness of (H)EVs

(H)EVs have been measured to emit approximately 3 to 20 dB(A) lower SPL than ICEVs of similar specifications when running at speeds below 20 kph [9], [10]. The low level of (H)EV exterior sounds may be advantageous from the viewpoint of traffic noise reduction and its related health benefits. However, the share of (H)EVs" in current vehicle fleet is too low that such benefits may not be realised until 2030 or later [40]. Currently pedestrians, cyclists, runners, and other road users, particularly the visually impaired, who rely heavily on sounds to detect traffic, may not be able to detect (H)EVs in sufficient time to prevent collisions. Here onwards, people with low to no vision are referred together as "visually impaired". Therefore, the (H)EVs may pose a threat towards the safe travelling of these pedestrians and other vulnerable road users. The problems to the safe travelling of road users due to the "quietness" of these (H)EVs, is referred to in the literature as the "**quiet vehicle problem**".

A literature review was carried out using a variety of databases such as Google Scholar, Science Direct, and Web of Knowledge using key words such as 'quiet vehicle', 'electric vehicle sounds', 'hybrid vehicle sounds', 'warning sounds' etc. Additionally, news articles and websites of organisations such as UNECE's working party on noise (GRB) and National Federation of the Blind (NFB) were also reviewed. The literature review reveals that the quiet vehicle problem dates back to late 20th century which is also marked by an increase in the (H)EV sales and usage. It is observed that communities and advocacy groups for the visually impaired have played an active role in raising concerns of pedestrians' safety due to 'quiet vehicles', and in driving research towards this issue. The rest of the section is divided into sub-sections where 2.2.1 chronologically discusses the resolutions and concerns raised against the quiet vehicles. The remaining sub-sections (2.2.2 to 2.2.4) thematically summarise the research activity towards quiet vehicles and the pedestrians' safety issue.

2.2.1. Concerns raised by blind community

Initial concerns about pedestrians' safety due to the 'quietness' (H)EVs were raised towards the end of the 20th century as evident from the resolutions passed by the Association for Education and Rehabilitation of the Blind and Visually Impaired (AER) in 1996 and 2000 [12], [13]. These resolutions state that visually impaired rely on traffic sounds to determine the state of traffic, the configuration of streets and intersections, in order to identify a safe time to cross. Moreover, the traffic sounds help them align and maintain a straight path of travel while crossing, thus an increase in the number of (H)EVs, which have relatively no motor sound compared to ICEVs make the task of travelling and crossing very difficult for visually impaired pedestrians [12], [13]. AER also commented that research is necessary to determine minimum acoustic cues required for pedestrians (including visually impaired) to travel quickly and safely in the presence of traffic and alternate techniques to accomplish this task.

Soon other advocacy groups for the visually impaired began identifying and raising concerns towards the quiet vehicle problem with National Federation of the Blind (NFB) playing the most influential role. Arguably, this problem is not limited to the visually impaired pedestrians who largely depend on traffic sounds but also to other sighted pedestrians who use such sounds in combination with other techniques to travel independently and safely [15]. In particular, elderly and people with hearing impairment could be at a higher risk, but there is no concrete research or accident statistics that confirms this.

A series of resolutions were passed between 2000 to 2010 [14]–[16] urging the US Department of Transportation and other transport research bodies in and around US to sponsor research that investigates the effects of (H)EVs on pedestrians' safety. These resolutions also urged for research into alternate solutions which would provide acoustic information equivalent to a vehicle's engine sound [14]–[16]. Later, a vehicle-based solution that would emit sounds while in operation was proposed upon collaborative discussions with researchers, automotive manufacturers, orientation specialists and representatives of visually impaired [16], [41]. Since then, NFB has played a major role in lobbying the automotive manufacturers, legislative bodies and researchers to drive research into the quiet vehicle problem and come up with specifications for adding sounds to vehicles.

2.2.2. ICEVs versus (H)EVs: Accident statistics

The concerns raised by communities and advocacy groups for the visually impaired have led to the worldwide research on the quiet vehicles. The intensity of this research is reflected in the fact that 'quiet vehicle problem' has become a part of the agenda for the Working Party on Noise (GRB), within the UNECE, since 2009. An informal group called "Quiet Road Transport Vehicles (QRTV)" has been established within the UNECE's GRB in 2010 to research and propose solutions to quiet vehicles[22]. Similar national groups have been established in USA, Japan, and the UK [38], [42], [43]. To begin with, these organisations have analysed the accident statistics to answer the question: "*if (H)EVs are more likely to collide with a pedestrian compared to ICEVs under similar traffic conditions?*"

National Highway Traffic Safety Administration (NHTSA) developed a research plan titled 'Quiet Cars and the Safety of Blind Pedestrians' [42], [44], under which it has analysed the pedestrian-vehicle collisions in 12 states of the US between 2000-2007. NHTSA defines an indicator called 'incidence rate of pedestrian/bicyclist crashes' as: "*the number of vehicles of a given type involved in crashes with pedestrians or bicyclists under certain scenarios, divided by the total number of that type of vehicle that were in any crashes under the same scenarios*" [39:8]. The scenarios constituted accident location; speed limit at the accident location; light and weather condition during collision; vehicle manoeuvre prior to collision. NHTSA found that for the analysed data (H)EVs had overall significantly doubled the incident rate of pedestrian/bicyclist crashes than ICEVs at speeds below 56 kph [10], [44].

This accident analysis by NHTSA has been criticised, particularly as the data does not indicate to what extent the absence of sound is responsible for higher incident rate of HEVs [40]. It has also been argued that the difference in "parameters" like the driving behaviour, mileage, and usage pattern of the two vehicle types may influence the results in favour of HEVs having higher incident rates [18], [40]. However, there is no clear evidence to support the previous statement.

It is observed that apart from the number of pedestrian crashes, incident rates also depend on the total number of crashes for a particular vehicle type. Sandberg et al. (2010) [18] claim that HEVs are most likely to have much fewer total number of crashes relative to ICEVs thus resulting in a higher incident rate of pedestrian/bicyclist crashes. To support this claim Sandberg et al. (2010) conclude that:

> *... until the end of the period 2000- 2007 it was still a little "exclusive" to own such a vehicle [HEVs] and it is reasonable to assume that the majority of drivers would be people with some extra concern for the environment; usually implying that they would also drive more carefully than most other drivers. It would not be surprising if this would mean that the number of crashes of such vehicles would be lower than for the ICE vehicles if calculated in relation to the traffic work [mileage] that they actually did* [17:3].

> *... vast majority of [(H)EVs] in the NHTSA study are of Japanese production and were only a few years old in this study, most of them only 1-2 years old. The authors expect that these new Japanese vehicles would meet higher safety standards, than the probably much older mix of ICE vehicles* [17:3].

However, the above statements are self-contradictory because if in fact the reasons given do reduce HEVs total crash rate then it should also reduce the collision rate with a pedestrian/bicyclist by comparable amount thus nullifying the overall change in incident rates.

To support the bias in the incident rates due to the usage pattern Verheijen and Jabben (2010) argue that HEVs are driven more in urban areas and their owners submit accident claims at a higher rate than the owner of ICEVs. Similarly, it is argued that HEVs are driven at low speed zones (less than 56 kph) more frequently than ICEVs which may introduce a stronger bias towards lower speeds [18]. But again, accidents at low speeds likely have less injuries or vehicle damage therefore the road users/drivers do not always submit an accident report [40]. Department for Transport in UK (DfT) also mention that people have the tendency of only reporting fatal accidents and the majority of non-fatal accidents especially involving a minor collision at low vehicle speeds remain unreported [45]. Thus, the actual accidents at low speed condition are likely to be much larger than the statistical data available.

To conclude the ‘incident rate’ [10], [44] is not a perfect indicator to determine the overall likelihood of an (H)EV or an ICEV to crash with a pedestrian/bicyclist in a given scenario as it depends on the total number of crashes. For instance a higher value of incident rate of pedestrian crashes means: Given that a particular type of vehicle is involved in any general crash, it is more likely to involve a pedestrian. Moreover, the crash data does not give evidence that the reason for greater pedestrian crash rate of HEVs is due to the absence of sound.

If we assume drivers’ skills and other parameters responsible for a crash to be similar for (H)EVs and ICEVs, an ineffective communication/interaction between the driver/vehicle and the pedestrian/bicyclist could be a major factor for a higher incident rate. The lower level of exterior sounds of (H)EVs compared to ICEVs could be a potential reason for pedestrian/bicyclist not noticing the vehicle thus resulting in their greater likelihood of crash.

Table 2.1 and Table 2.2 present the NHTSA’s crash data analysis [44] by considering only “critical manoeuvre” i.e., where the incident rates for HEVs are relatively higher than ICEVs (greater than 1.5 times in most cases). From the tables, it is observed that HEVs are twice as likely to collide with a pedestrian in the combined vehicle manoeuvres of slowing/stopping, starting in traffic, backing, and making a turn. Similarly, HEVs are twice as likely to collide with a bicyclist in the combined vehicle manoeuvres of entering/leaving a parking space/driveway, slowing/stopping, going straight and making a turn.

Table 2.1 Pedestrian-vehicle collisions at critical manoeuvre as analysed by NHTSA, 2009 [44]

Vehicle Manoeuvre	HEV crashes			ICEV crashes		
	No. of Pedestrian Crashes	Total no. of HEVs	Incident rate of pedestrian crash	No. of Pedestrian Crashes	Total no. of ICEVs	Incident rate of pedestrian crashes
Making a turn	19	1061	1.8%	698	70245	1%
Slowing/ stopping	6	1137	0.5%	148	70872	0.2%
Backing	7	132	5.3%	261	9093	2.9%
Starting in traffic	3	102	2.9%	50	4168	1.2%
Total	35	2432	1.4%	1157	154378	0.7%

Table 2.2 Bicyclist-vehicle collisions at critical manoeuvre as analysed by NHTSA, 2009 [44]

Vehicle Manoeuvre	HEV crashes			ICEV crashes		
	No. of Bicyclist Crashes	Total no. of HEVs	Incident rate of bicyclist crash	No. of Bicyclist Crashes	Total no. of ICEVs	Incident rate of bicyclist crashes
Going straight	22	3667	0.6%	873	261522	0.3%
Making a turn	14	1061	1.3%	659	70245	0.9%
Slowing/ stopping	3	1137	0.3%	101	70872	0.1%
Entering/ leaving parking space/ driveway	3	83	3.6%	20	5870	0.3%
Total	42	5948	**0.7%**	1653	408509	**0.4%**

In the UK, Transport Research Laboratory (TRL) has performed a similar analysis of vehicle accident statistics in association with the Department for Transport (DfT), UK. TRL reviewed the Great Britain data called STATS19 on road casualties for period 2005-2008 [38]. Accidents have been analysed for the categories of ICEVs and (H)EVs. For comparison with NHTSA's results only passenger cars, car derived vans and vans with gross vehicle weight under 3.5 tonnes have been included in the analysis. In addition, only the vehicles that physically collided with a pedestrian have been included to calculate pedestrian crashes. Table 2.3 shows a comparison between the overall incident rates for pedestrians' crashes from NHTSA and TRL's analysis.

Table 2.3 A comparison of incident rates for pedestrians' crashes for the accident analysis by NHTSA and TRL [38]

Scenario under consideration	US data (NHTSA)		GB data (STATS19)	
	Hybrid vehicles only	ICE Vehicles	Electric and hybrid vehicles	ICE Vehicles
Total No. of cars involved in accidents	8,387	559,703	495	737,655
Number of cars resulting a pedestrian casualty	77	3,578	61	63,575
% of cars involved in accidents resulting in a pedestrian casualty	0.9%	0.6%	12.3%	8.6%

The above results suggest an increase in pedestrians' risk to safe travelling due to (H)EVs compared to ICEVs. However, analysing the TRL data for total number of vehicles registered for 2005-2008 in the UK reveals contradictory results. Table 2.4 compares the pedestrian collision rate and overall accident rate for (H)EVs and ICEVs relative to the number of vehicles registered.

Table 2.4 : Comparison of the pedestrian collision rate and overall accident rate relative to the number of vehicles registered for (H)EVs and ICEVs in the UK between 2005-2008 [38]

DfT data	HEVs	ICEVs
No. of vehicles that collided with a pedestrian	61	63575
No. of vehicles involved in all types of accidents	495	737655
Number of vehicles registered	107122	111183413
Rate of pedestrian collision/ 10000 vehicles	**5.7**	**5.7**
Rate of accidents/ 10000 vehicles	**46.2**	**66.3**

Except for the US and the UK, no significant accident data are available in other parts of the world that can confirm that (H)EVs are more likely to collide with pedestrians or bicyclists compared to ICEVs. Even in the presented accident statistics, (Table 2.1 to Table 2.4) the (H)EVs constitute less than 0.1% of total vehicle fleet. Thus, currently it may not be fair to make such comparisons as that very small percent of (H)EVs are still very exclusive and their usage patterns may also vary thus introducing a bias to comparisons.

Reviewing the police reports of road casualties available from the DfT, UK website it is observed that 38% of all road accidents in 2009 involved the failure of the drivers to look properly [45]. In addition 58% of accidents involving pedestrians reported that the pedestrians failed to look properly while only 31% of those cases report carelessness or a haste in part of the pedestrian [45]. This means that for the rest 69% of the cases the pedestrian being careful enough was still unable to look or detect a vehicle on time to avoid an accident. The road causalities data for the years from 2007 – 2009 all involve failure to look as the major reason [45]–[47].

Therefore, presence of cues other than the sight is necessary for pedestrians both sighted and visually impaired in order to detect a vehicle.

2.2.3. Extent and intensity of the Quiet Vehicle Problem

Much research has been conducted to support the claim that absence of sound in vehicles may pose safety risk to pedestrians and other road users. In general, researchers have investigated if there is a significant difference in detection of (H)EVs from ICEVs and if this difference may pose a risk to pedestrians. This detection data is then compared to the difference in the acoustic and psychoacoustics values of the exterior sound measurements of the corresponding vehicles. Such studies measure detection using following performance variables:

I. ‘time to vehicle arrival’: the time from first detection of an approaching vehicle to the time when the vehicle passed in front of the pedestrian [10], [48].

II. ‘detection distance’: distance between the vehicle and the pedestrian location at the moment the pedestrian indicates detection [9], [31]–[33], [35], [49].

JASIC have found that the pass-by SPLs of HEVs in EV mode is significantly lower than ICEVs when measured at a distance of 2 m from the line of vehicle travel [9]. The SPL difference decreases with increase in vehicle speed becoming negligible beyond a speed (“**crossover speed**”) of 20 kph [9]. This SPL difference corresponds to the laboratory listening tests that reveal that HEVs (in EV mode) take significantly longer to detect than ICEVs up until 20 kph speed [9]. Figure 2.1and Figure 2.2 show the results of the study by JASIC.

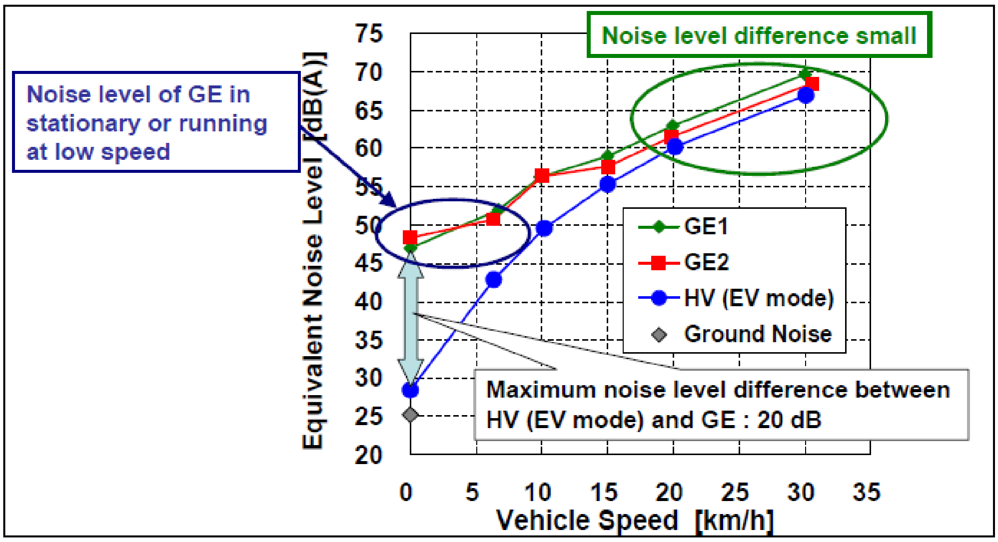


Figure 2.1 Pass-by dB(A)$_{eq}$ measured at 2 m from the centre of an HEV (here "HV") and two ICEVs (here "GE1" and "GE2") in Japan [9].

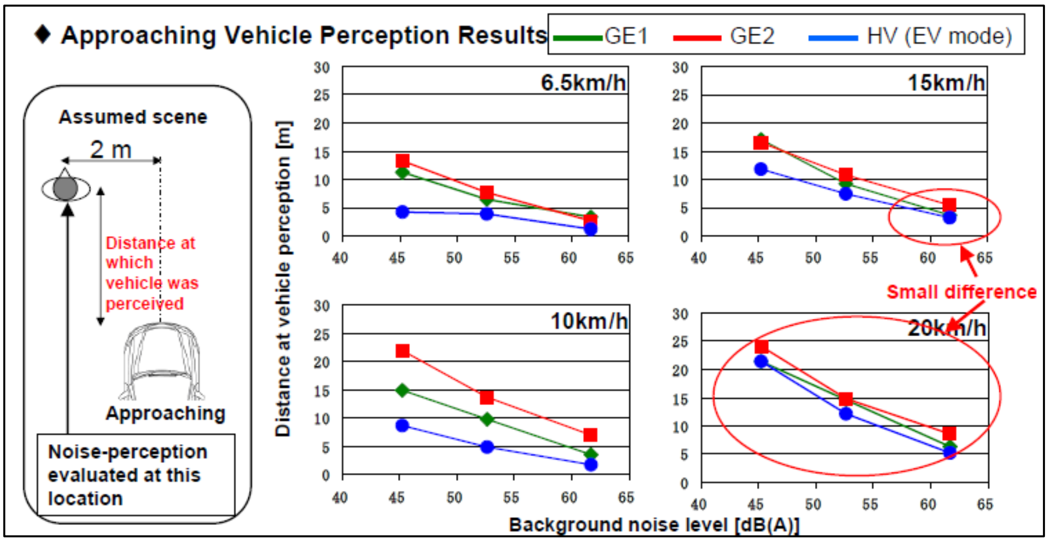


Figure 2.2 Results of a study on perception of sound from an approaching HEV car (here "HV"), compared to two ICE cars ("GE1" and "GE2") in Japan [9].

Following this, NHTSA conducted research on the orientation and mobility needs of visually impaired pedestrians and the strategies used by them during navigation in a traffic environment. This led them to conclude the following vehicle operating conditions as "**critical safety scenarios**" for such pedestrians [10]:

Vehicle backing out at 5 mph [≈ 8 kph] (mimicking a vehicle backing out of a driveway); vehicle slowing from 20 to 10 mph [≈32 to 16 kph] (mimicking a vehicle preparing to turn right from the parallel street); vehicle approaching at constant low speed [(5-6 mph), ≈ 8-10 kph]; vehicle accelerating from a stop; and vehicle stationary (such as at a stop light) [10:1-2].

Figure 2.3 shows the NHTSA results on SPL measurements and detectability tests for three such scenarios. It was observed that SPL difference for HEVs and ICEVs becomes negligible after 32 kph (20 mph) ("crossover speed"). Thus they concluded that additional acoustic cues are required only for speeds below 32 kph [10], [50].

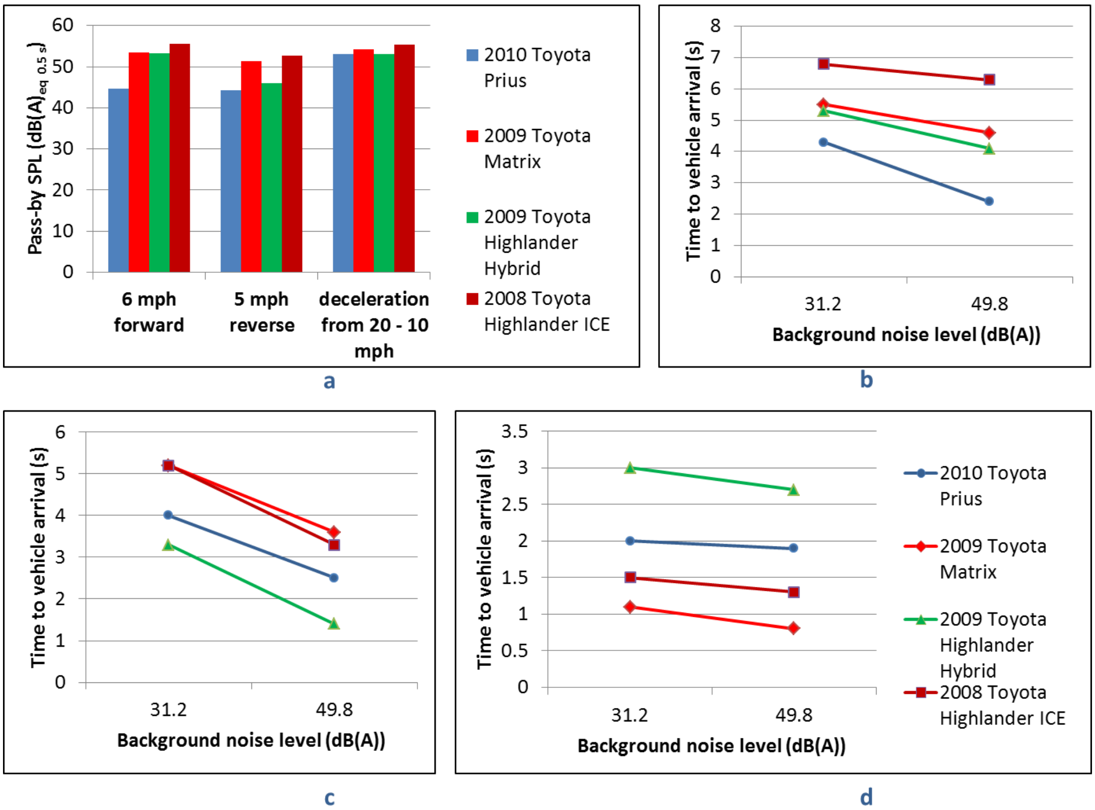


Figure 2.3 Results of study by NHTSA (2010) [10]. **(a) Pass-by dB(A)$_{eq}$ of 2 ICEVs and 2 HEVs measured at a distance of 3.7 m from the centre of each vehicle. (b), (c) and (d) are results of listening tests for 6 mph (10 kph) forward pass-by, 5 mph (8 kph) reverse pass-by and 20 to 10 mph (32 to 16 kph) deceleration**

Similarly, a research under the National Institute for Public Health and the Environment, the Netherlands suggests that response time for a conventional passenger car is reduced from 1.6 s to 0.7 s under the absence of engine noise at speeds of 15 kph and background noise of 60 dB [40]. Further, the difference in detection decreases with increase in speed possibly because tire-road interaction noise increases at a greater rate than the engine noise with increase in speed and above 30 kph it dominates the total vehicle noise [51].

In 2011, the Transport Research Laboratory (TRL), in the UK carried out a similar research as NHTSA involving SPL measurements and detection tests of four (H)EVs and four ICEVs of similar size and type [38]. Contrary to the previous results, TRL did not find a significant SPL difference between the ICEVs and the equivalent (H)EVs (see Figure 2.4).

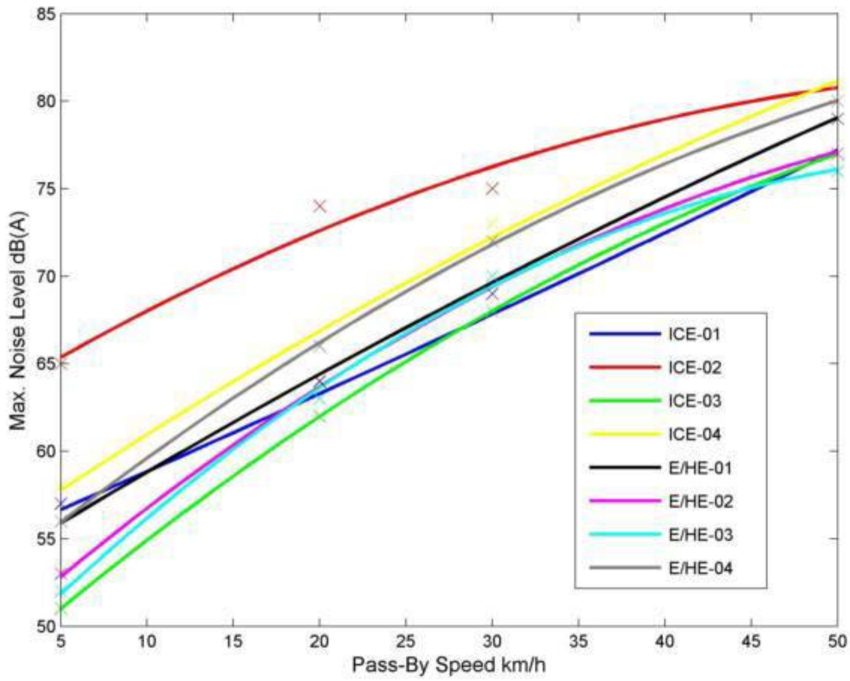


Figure 2.4 Pass-by SPL in dB(A) measurements of four ICEVs (here "ICE") and four (H)EVs (here "E/HE") at 1.8 m from the vehicle centre, in the UK [38].

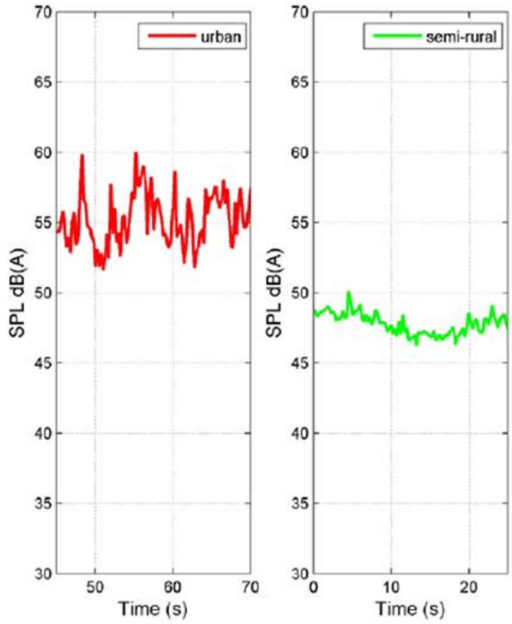


Figure 2.5 Background noise used in the listening tests conducted by TRL, UK [38]**.**

	Total events	% of events with increased risk exposure		
		'Semi-rural' environment	'Urban' environment	All environments
ICE vehicles	440	12.3 %	22.3 %	15.0%
E/HE vehicles	240	17.3%	28.9%	21.7%
Relative risk for E/HE vehicles		1.4	1.3	1.4

Figure 2.6 Results of the listening tests conducted by TRL, UK [38]**.**

TRL's laboratory listening tests used the values of safe stopping distance defined in the UK Highway Code (DfT and Driving Standards Agency , 2007) to calculate an indicator called "**increase in risk exposure**". With an assumption that there will always be some element of risk, however small, for crossing pedestrians whenever traffic is present on the road, they define an increase in risk exposure whenever a vehicle is detected at a distance less than the safe stopping distance or not detected at all. The listening tests were performed at two background noises namely 'semi-rural' and 'urban' (see Figure 2.5) for vehicle manoeuvres namely, 7-

8, 20, 30 and 50 kph pass-bys; acceleration from stop at: 0.5 m/s^2 and 1 m/s^2. Results showed that in both background noises the increase in risk exposure for (H)EVs is 1.4 times and 1.3 times higher than ICEVs respectively (Figure 2.6). Importantly, for pass-by at 7-8 kph in a semi-rural background noise increase in risk exposure is 4 times higher for (H)EVs (40% compared to 10%) while it is 2 times higher for (H)EVs in urban background noise (80% compared to 40%). Detection results (increase in risk exposure) are similar for both (H)EVs and ICEVs at or above speeds of 30 kph. In semi-rural background noise, when vehicle accelerated from stop at 0.5 ms^{-2} the increase in risk exposure is 6 times higher for (H)EVs. However, due to only few participants (n=10) results may not represent the demographics of the visually impaired in the UK, but only give an initial indication of risk to pedestrians' safety due to (H)EVs. Moreover, in this study, the number of tests performed for each manoeuvre and vehicle type was not uniform, and for some vehicle manoeuvres, no listening tests were performed. Therefore, the detailed results of every vehicle manoeuvre have not been presented.

2.2.4. Solution to quiet vehicle problem

Since visually impaired are most at risk due to 'quietness' of (H)EVs therefore most of the solutions proposed cater to their needs. The possible solutions to the quiet vehicle problem can be broadly classified as: infrastructure-based, education and enforcement based, environmental regulations, pedestrian-based, vehicle-pedestrian based and vehicle-based [10]. A brief summary of the major solutions with advantages and disadvantages is presented below:

Infrastructure-based solutions include use of accessible pedestrian signals for signalised intersections that can inform pedestrians of a safe time to cross in nonvisual formats [10]. Such solutions also include use of automatic pedestrian detection systems for uncontrolled approaches that alert the drivers using flashing lights about the presence of a pedestrian [10]. An obvious advantage here is that no extra noise is produced but they require very long implementation times and huge capital investments if such systems are to be installed at every intersection and junction. Moreover, visually impaired doubt the effectiveness of such systems as they may not be applied over more than a very small fraction of possible locations of pedestrian-vehicle interaction [10]. Additionally they do not provide enough information on the vehicle speeds and manoeuvres [10]. Nagahata (2011) propose a similar solution as a proper design of intersections and crossings with adequate separation between vehicle and pedestrian routes and use of separate traffic signals for pedestrians [52]. Here again, the installation is costly and has a long implementation time.

Education and enforcements based solutions include orientation and mobility training programs for visually impaired but independent travellers and service animals such as guide dogs [10]. Other researchers propose better training of quiet vehicle drivers to educate them about the quite vehicle problem and how they can be more responsible and alert to avoid pedestrian collisions [18], [19]. Many such programs are already available and some researchers especially the advocacy group for visually impaired consider that these measures may not have potential to provide further safety benefits [10]. Moreover, these measures are essentially limited to the visually impaired independent travellers.

Environmental regulations include initiatives to lower overall traffic noise levels, ambient sound levels, and reducing noise emissions of current and future vehicles [10], [18], [19]. These measures are more suitable as a long-term solution as they reduce overall noise pollution. This helps reduce the masking from relatively louder sound sources thus improving the relative detectability of the quiet vehicles. However, these measures require long implementation time and face more difficulties in full implementation given the numerous and unmanageable ambient sound sources for e.g. construction, industry, traffic, recreational, animal and nature.

Pedestrian-based solutions like use of electronic devices (hand-held or attached to a cane) that produce tactile/audio output upon a vehicle's approach may prove useful as they can be easily implemented and provide more acoustic cues (like distance and direction of vehicles) than the aforementioned solutions. But there is a strong objection from the visually impaired community on this matter [10]. They, and sighted pedestrians, are not in favour of carrying a detection device every time they step outside the house.

The pedestrian-vehicle proximity based devices include proximity warning systems like a pedestrian-held transmitter and a vehicle-mounted receiver [10], or "autonomous emergency braking systems" [19] that induce a brake upon detecting a pedestrian proximity. These measures may be more effective as it can alert both a pedestrian and a driver about a potential conflict but it requires an integration with vehicle system [10]. It is currently difficult to implement on every vehicle and every pedestrian and increases vehicle cost. Just like the pedestrian-based solutions, both pedestrians and drivers are also opposing the pedestrian-vehicle based solutions.

Vehicle-based solutions include installation of devices in vehicles that emit additional warning sounds. These simulated sounds should ideally provide same minimum amount of information as provided by ICEVs. Two options have been explored: to have simulated sounds only when a vehicle operates below the 'crossover speed'; or to have other types of audible signals (beeps, horns, etc.) that activate only in response to a wireless signal from a transmitter carried by a pedestrian who wants to be alerted of the vehicle presence [10]. The former eliminates the need for a person to carry a transmitter every time while walking on-road and provides acoustic cues to alert every road user (pedestrian, cyclists, runners, animals, and other car drivers) and not just a specific pedestrian. The latter however, does avoid a generation of sound at all times even when no other road user may be present, thus keeping extra noise to the minimum. However, beeps, alarms etc. may not provide the necessary information about the vehicle speed, acceleration and manoeuvre. Both options will lead to an increase in the vehicle cost and the drivers may not like it.

Legislations now mandate vehicle-based solutions (see section 2.3) but these are facing criticism by environmentalists and soundscape specialists because this may contribute to noise pollution. However, humans are very sensitive towards approaching sounds therefore, only subtle enhancements to the current (H)EV sounds below ‘crossover speeds’ or under some critical manoeuvers should be sufficient [53]. Some also argue that heavy masking sounds like construction noise would render the warning sounds useless in their presence [52]. However, the strategy adopted by visually impaired is to cross when it is quiet and no masking sounds are present [10] therefore sounds added need not be loud enough to be heard in the presence of all masking sounds. An in-depth research is required to develop specifications for the new (H)EV sounds.

2.3. Legislation for (H)EV Sounds

Laws have been enacted worldwide for (H)EV sounds. Japan’s Ministry of Land, Infrastructure, Transport and Tourism have mandated that (H)EVs be fitted with a sound generating device. This device is called an “Approaching Vehicle Audible System” (AVAS) which emits sounds to inform pedestrians and other road users of the vehicle’s approach to avoid a potential collision [21]. The Pedestrian Safety Enhancement Act of 2010 was the first public law in the USA that directed the US department of transportation to establish a safety standard for (H)EVs for alerting the pedestrians of the vehicles’ operation [20]. Consequently, in 2013, the US government has issued a Federal Motor Vehicle Safety Standard (FMVSS) that mandates these vehicles be fitted with devices that emit sounds to alert pedestrians, and other road users of the vehicles’ approach [24]. A similar standard, called Global Technical Regulation (GTR), has been formulated by the UNECE [25]. Like Japan, the UNECE also mandates an “Audible Vehicle Alerting System” (AVAS) for (H)EVs in Europe [23], [25]. GTR states the harmonized operational criteria and acoustic specifications of AVAS for Europe [25].

(H)EVs’ inherent sound level, however, increases with speed as the tyre-road interaction sound becomes dominant thereby eliminating the need for an additional sound to aid detection of these vehicles at higher speeds [9], [10], [21], [24], [25]. The existing variety in (H)EV models and specifications causes variation in their inherent sound level, which in turn varies the speed at which (H)EV become audible “enough” compared to ICEVs. Current legislations are therefore less specific and recommend that additional sounds should be emitted continuously till the vehicle attains a speed somewhere between 20 to 41 kph and at idle and reverse [21], [23]–[25].

2.4. (H)EV Sounds: NVH Challenges

Legislations specify that (H)EVs use vehicle-based devices to generate sounds [21], [23]–[25]. These (H)EV sounds will face the following NVH challenges.

2.4.1. Pedestrians' safety

Firstly, and most importantly the (H)EV sounds should be detectable enough to make pedestrians aware of the vehicle's approach in sufficient time for them to be able to avoid a potential collision.

2.4.2. Brand reinforcement

However, an area that remains overlooked by the policy makers is that these sounds will influence people's impressions about the vehicle brand. A vehicle's sound has always been an important characteristic for reinforcing the brand image of the vehicle (see section 2.5.1). Enhancing a vehicle's sound quality to influence and increase customer satisfaction has been an integral part of the automotive design process [26]–[30]. People hearing the exterior sounds could evaluate the vehicle as a brand, in terms of simply liking to hear the vehicle pass-by, or as a potential consumer who may want to purchase the vehicle. Therefore, vehicle manufacturers want the (H)EV sounds to promote positive impressions of the vehicle brand [26].

2.4.3. Soundscape benefits

Traffic noise is one of the major sources of noise pollution, and particularly effects health and quality of life of the residents near traffic areas. The common health related effects of traffic noise are annoyance, sleep disturbances, stress and reduced speech intelligibility, concentration and task performance [54]. Introduction of (H)EV sounds on a mass scale will heavily influence the urban soundscapes. These (H)EV sounds must not increase the existing traffic noise related annoyance and health problems. As public, we do not want to lose the soundscape benefits of the current 'quietness' of these vehicles. Therefore, it is important to ensure that these sounds have an overall neutral or positive effect on soundscapes.

Safety, brand, and soundscapes are the competing criteria for the evaluation of (H)EV exterior sounds. Figure 2.7 shows the NVH challenges of the (H)EV sounds along with the concerned stakeholders and beneficiaries.

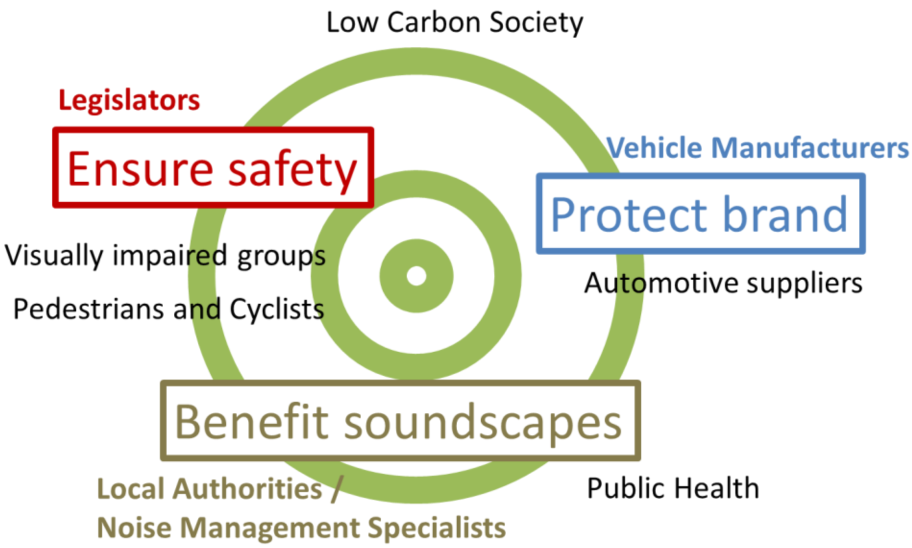


Figure 2.7 The NVH challenges of (H)EV sounds

2.5. Automotive Sound Quality: Terminologies

This section introduces the basic terminologies used within the area of automotive sound quality as relevant for this research.

2.5.1. Sound Quality and its influence on brand

Sounds are an important characteristic of a product and may be used to enhance the experiences of the customers who use the product [26], [27], [29]. Sound quality is defined as the perceptual reaction to the sound of a product [55]. Thus, overall sound quality relates to the subjective (emotional or perceptual) responses to the sound [55]. Sound Quality Engineering therefore refers to tailoring and enhancing a product's sound in order to enhance customer experiences or meet or exceed customer expectations [26], [29].

Sound quality research is an essential part of the NVH process within the automotive industry. A vehicle's sound influences the perception of the vehicle brand. It plays a key role in identifying and distinguishing the brand of the vehicle [26], [27]. This could be shown with examples such as Jaguar cars or Harley Davidson motorcycles where sound is a key aspect in identifying, recognising and distinguishing the vehicle brand from other competitor vehicles [26], [27]. Therefore, enhancing and tailoring the vehicle sound quality is a key technique for vehicle branding [26]–[30]. Enhancing a vehicle's sound quality to influence and increase customer satisfaction has been an integral part of the automotive design process [26]–[30].

2.5.2. Emotional dimensions of sound quality

Sound quality, being subjective in nature, is usually captured through a set series of adjectives that can be used to describe the character of the sound [26]. These adjectives, referred to as "**semantics**", describe the emotional responses to a product sound using emotional or feeling-related words such as powerful, pleasant, comfortable, annoying, refined and harsh [26], [56].

Similarly, in automotive sound quality several semantic descriptors are used to convey impressions of, or emotional responses to the vehicle brand from listening to its sound [26]. In many experiments, researchers have collated a list of these semantic descriptors and used them to evaluate the nature of the vehicle sound quality [26], [28]. Then, using principal component analysis, researchers have combined the most common semantic descriptors of vehicle sound quality into two or three emotional dimensions of vehicle sound quality [26], [28], [57].

Emotional dimensions are defined as a linear semantic space [26] where extremities of each semantic space are defined by two bipolar adjectives such as, unpleasant-pleasant or weak-powerful [26]. Every emotional dimension is expressed using a semantic differential scale (see section 2.6.4.2) that measures the perceived level of the semantic pair it represents [26]. For example, an emotional dimension of weak-powerful would measure the perceived level of a product being powerful using numerical values on the semantic differential scale. The principle behind this approach is that the perception of a stimulus falls into two to three standard emotional dimensions that distinguish the product sound quality [26], [56].

2.5.3. Psychoacoustic metrics

As discussed in section 2.5.1, sound quality is essentially a study of the perception of, or the emotional responses to sound. Therefore, in sound quality research many metrics have been devised that correlate with how humans perceive sounds. These metrics are often referred to as psychoacoustic metrics [11]. The key psychoacoustic metrics in automotive sound quality are defined below [11]:

I. A-weighted decibels (dB(A)): Human ear sensitivity to noise is strongly dependent on frequency. Average human hearing range falls within 20 to

20,000 Hz [11]. In general, a human ear is more sensitive to sounds in the middle frequency ranges 250 to 12,500 Hz, while sounds of lower or higher frequencies are perceived much lower than their actual SPL. Details of the human ear's frequency dependency on the perception of intensity and loudness of sounds is given by Fastl and Zwicker (2007) [11]. A-weighted decibel or dB(A) is obtained by applying a frequency weighting to the original sound signal to conform to the frequency response of the human ear. In this weighting, higher and lower frequencies are attenuated and middle frequencies remain almost same to the original sound signal. Thus, SPL in dB(A) mimics the human ear dependency on the frequency of an acoustic signal, hence it gives the magnitude of the sound as perceived by the human ear.

II. Loudness: It relates to how strong a human ear finds a sound [11]. It is essentially a psychological correlate of the physical strength (amplitude) of the sound. Mathematically, the loudness of a sound is expressed in the units of sones (details in [11]).

III. Sharpness: It is the subjective perception of how sharp is a sound. It is a measure of the high frequency content of a sound, the greater the proportion of high frequencies the 'sharper' the sound. Mathematically, the sharpness of a sound is expressed in the units of acum (details in [11]).

IV. Roughness: It is the subjective perception of roughness or unevenness of a sound. In psychoacoustics roughness quantifies the subjective perception of rapid (15-300 Hz) amplitude modulation of a sound and is measured in aspers (details in [11]).

2.6. Automotive Sounds' Evaluation Methods: State-of-the-art

From the previous discussion, it can be inferred that evaluating (H)EV exterior sound quality requires more than the measurement of objective metrics by pass-by noise tests. It requires an evaluation that tests the sounds for safety of the pedestrians while ensuring that: it meets the legislative guidelines, enhances brand quality, and at the same time has overall neutral or positive effects on the soundscapes. This, in turn, calls for appropriate sound quality evaluation methods that assess these (H)EV sounds on the criteria discussed in section 2.4. This section critically reviews the state-of-the-art methodologies and approaches of automotive exterior 'sound quality evaluation' (detection and perceptual evaluation of subjective attributes). The major aspects of any listening evaluation are: the listening environment during the evaluation, participants used as evaluators, stimuli preparation and delivery, measurement scales for data collection, and analysis methods [58], [59]. These aspects are dependent on the purpose of evaluation [58], [59]. A thematic review of the state-of-the-art methodologies is presented in relation to these above aspects, and in the context of experimental design and cognitive psychology.

2.6.1. Evaluation environments

2.6.1.1. Traditional environments:

Traditionally, listening evaluations of automotive exterior sounds are usually conducted on-road or inside a laboratory. On-road evaluations involve driving the "**target vehicle**" − the vehicle being evaluated − emitting a sound, in urban town scenarios such as parking lots, crossroads and junctions [9], [31], [32], [36], [37] usually by reserving the test site to get no nearby traffic and very low background sound [31], [32], [35]. The participant usually sits on the pavement [9], [31], [35], [37] or occasionally stands as a pedestrian [36] and evaluates the sounds of the passing vehicle in real time while receiving visual and auditory stimuli of the urban ambience [9], [31], [32], [36], [37]; sometimes with additional vehicles, and other sound sources [31], [36]. This resembles the real life pedestrian-vehicle interactions where also a pedestrian experiences the electric vehicle's sounds in the presence of the mentioned stimuli. Here, due to the limited capacity of attention and human cognition, the pedestrian undergoes "divided attention" where his/her attention resources are divided among the various stimuli [60], [61]. Hence, on-road evaluations provide the correct context for evaluating vehicle sounds. However, they do not provide control on external factors, such as, changes in the background sounds, visuals, traffic, and weather [31], [36]. Therefore, it is difficult to maintain consistency and repeatability in the results. On-road evaluations also require long testing durations as it is difficult to maintain various driving conditions of the "target vehicle" while maintaining a similar ambience [31], [36].

Laboratory evaluations follow a similar process but inside a controlled environment. Here, a recorded vehicle sound is played in an anechoic room, usually using headphones or an array of speakers and participants' response collected based on their listening [9], [10], [33], [34], [37], [38]. This environment provides better experimental control [10], [33], [34], [37], [38]. Therefore, consistency and repeatability are improved and back-to-back comparative tests can be performed thereby reducing the experimental duration. However, conventional laboratory listening tests/ evaluations use a single stimulus (target vehicle's sound) and so they lack the appropriate context. Here, the listener undergoes a "focused auditory attention" where his/her attention is focused on the target vehicle sound and information from other stimuli (if any) is ignored [60]. Evaluation of the sounds is influenced by the mode of processing information received from various stimuli during decision making, which in turn is affected by a listener's state of attention [60], [61]. Thus, correct context is important for a listening evaluation to obtain results representative of real life situations.

2.6.1.2. Virtual Environments (VEs):

A VE can be defined as an environment that is realized through computer-controlled display systems that create an illusion of being in another physical place or environment that the VE simulates, even when one is physically situated in another place or environment [62], [63]. An immersive VE creates a feeling of 'presence' which is defined as: "experiencing the computer-generated environment rather than the actual physical locale" or; the "sense of 'being there'" in the place depicted by the VE rather than in the real physical place where the participant's body is actually located" [63], [64]. The most widely used VEs are multi-sensory immersive VEs that simulate multi-sensory information such as auditory and haptic information in addition to visual information [65], [66].

Over the past two decades, VEs have gained popularity in the field of education, healthcare and transportation research [66]–[68]. In these fields, VEs have proven to be an effective tool for improving learning, task performance and training [65]–[69]. Particularly in transportation research, immersive VEs have been shown to provide an appropriate context by simulating a realistic traffic environment using sounds and visuals [59], [70]–[73]. Simultaneously, the researcher can fully control the experimental conditions [59], [70]–[73]. Thus, VEs can bridge the gaps between the on-road and laboratory experiments.

Currently, most automotive NVH simulators create a VE from a driver's perspective [70]–[73]. The vehicle NVH simulators have been successfully used for evaluating vehicle interior sounds to assess impressions of the vehicle brand by both experts (vehicle manufacturers and NVH engineers) and non-experts (general public as potential customers) [59], [70]–[72]. The technique of simulating VEs from a pedestrians' perspective is very new in the area of automotive NVH. Although exterior sound simulators exist [74], the appropriate methods on using this environment for automotive exterior sound quality evaluations has not been fully investigated. It is expected that VEs should provide similar advantages in vehicle exterior sound quality evaluations.

2.6.2. Stimuli

2.6.2.1. Stimuli selection:

Section 2.2.3 identifies the most common scenarios for pedestrian-vehicle interactions that are critical to pedestrians' safety [10]. The scenarios primarily include vehicle manoeuvres at low speeds (below 48 kph) in locations such as straight roads, crossroads, T-junctions and parking lots [10], [44]. These scenarios are used in most on-road detection tests [9], [31], [32], [35]–[37] as they provide appropriate context for evaluations.

The new sounds for (H)EVs must satisfy the legislative guidelines. FMVSS recommends broadband low frequency sounds in the range 160 – 5000 Hz to enhance audibility [24]. GTR also recommends that these sounds include at least two 1/3 octave bands within the frequency range 50 Hz to 5 kHz [25]. FMVSS in the US has fixed their minimum sound level as 49 dB(A) at idle, 52 dB(A) at reverse, 55 dB(A), 62 dB(A) and 66 dB(A) at 10, 20 and 30 kph, respectively [24].

Japanese guidelines recommend limiting the sound level to that of a similar vehicle of the same category equipped with an internal combustion engine and operating at 20 kph [21]. For the latest Japanese and European vehicles this level is 62 to 66 dB(A) [9], [38]. UNECE and Japanese guidelines prohibit using siren, horn, chime, bell and emergency vehicle sounds; alarm sounds e.g. fire, theft, smoke alarms; intermittent sound; melodious sounds, animal and insect sounds; and sounds that confuse the identification of a vehicle and/or its operation [21], [25]. The current set of guidelines is not specific and is subject to change based on the new research data.

The choice of sounds is also governed by the purpose of evaluation [58]. Evaluations of a set of candidate electric vehicle sounds involves comparing the sounds against one another on some evaluation criteria [10], [31], [32], [35]. The audibility and hence the detection rate of the sounds depends on psychoacoustic metrics such as SPL in dB(A) and frequency spectrum [24], [25]. Similarly, dB(A), loudness, sharpness, and roughness metrics closely relate to emotional evaluations of automotive sounds [26]. Thus, literature considers SPL in dB(A), loudness, sharpness and roughness as the key psychoacoustic metrics in automotive sound quality [26]. Using sounds with sufficient variation in these metrics ensures these sounds will show enough variation in evaluation scores for a relative comparison.

2.6.2.2. Stimuli presentation:

During conventional laboratory detection tests of vehicle exterior sounds, a target vehicle sound is played as soon as a new experimental condition begins. Therefore, the vehicle could be heard arriving at the listener’s position always after a fixed length of time and usually from a fixed direction [9], [10], [33], [37], [38]. This may result in a bias due to practice effects where the participants start expecting the arrival of the target vehicle at a fixed time. This problem increases during detection tests using visual simulations, whereby a participant may associate the arrival of the vehicle with certain visual cues such as arrival at a crossroad. Therefore, the participant may pay more attention to detecting a vehicle's sound upon receiving those visual cues and may even falsely respond that (s)he has heard a vehicle approaching because (s)he expects the vehicle to arrive. This form of bias is specific to all listening studies involving vehicle detection and may result in incorrect detection times of exterior sounds. In real life, a target vehicle can approach a crossroad from any direction and at any time. These variations should be reflected in experimental designs, by altering the direction of approach and the arrival times of the electric vehicle to reduce expectation biases and make the scenarios more realistic, and thus more ecologically valid. This also allows their effect on participant evaluations to be examined.

2.6.3. Measures

2.6.3.1. Detecting the approach of target vehicle

Researchers mostly use the following measures to assess the sounds for their safety risk to pedestrians:

I. "**time-to-vehicle arrival**": the time from the first detection of the vehicle to the instance when the vehicle actually passes the pedestrian's location [10], [48].

II. "**detection distance**": distance between the vehicle and the pedestrian location at the moment the pedestrian indicates detection [9], [31]–[33], [35], [49].

2.6.3.2. Evaluating impression of the vehicle brand

Unlike the ICEV sounds, (H)EV sounds are not evaluated for their impression of the vehicle brand. For ICEVs, the impressions of the vehicle brand from listening to its sound is measured using standard emotional dimensions of vehicle sound quality [26]. These emotional dimensions distinguish and discriminate between the different types of car sounds [26], [28], [57] such as sounds of different characters like − 'luxury', 'sporty'; and sounds from different manufacturers [26], [28], [57]. Most automotive sound quality researchers use two underlying emotional dimensions - where one dimension describes the strength or the power aspect of the vehicle and the other describes the aspects related to comfort and pleasantness of the vehicle [26]. '**Powerful**' and '**pleasant**' are the most widely used emotional dimensions of automotive sound quality [26], [28], [56], [57]. These were developed after factor analysis of a large number of verbal descriptors for car sounds and together they explained 70% of the variance in emotionally evaluating numerous car sounds [28].

2.6.4. Measurement scales and data collection

2.6.4.1. Detecting the approach of target vehicle

Detection time/distance is measured accurately and conveniently measured in a laboratory/ listening room. Here, a participant is usually asked to press a button to detect the vehicle, and the entire process from the play of vehicle sound until the pressing of the button is time marked [10], [31]. On the other hand, it is difficult to implement an accurate vehicle-detection-measurement-method on-road, in the real world. During on-road vehicle detection studies, the detection-measurement-method is a trade-off between accuracy, cost, feasibility, and installation issues. Most of these methods are inaccurate, but economical, and involve participants raising hands to indicate vehicle detection, video recording the experiment to check target vehicle's position w.r.t road markings to estimate the detection distance [31], [32], [35], [37]. More accurate methods involve marking instances of detection using push buttons and monitoring target vehicle's position using photoelectric sensors laid along the road, and storing the data in a software that is synchronized with the experiment process [31], [35]. However, these methods are relatively costly and difficult to implement and could have their own errors and problems.

In real world traffic scenarios, the ambient soundscapes includes variety of vehicular as well as non-vehicular sounds. Here, pedestrians have to identify and detect the vehicle in the presence of other non-vehicle based ambient sounds. It is likely that in the real world vehicle detection could be a more constant and subjective process [10]. However, currently there is no clear understanding or evidence to how and why pedestrians make errors, if any, in detecting a vehicle in the real life. If a similar non-stationary real world ambient soundscape is introduced in a vehicle's listening evaluation, it is very likely that participants may confuse fluctuations in the ambient soundscape with an approach of a vehicle. Thus, the detection measurement method could include an option for participants to re-detect the target vehicle if they think they made mistake detecting the vehicle previously. This would also monitor how frequently pedestrians have tendency to make detection errors, if any.

2.6.4.2. Evaluating impression of the vehicle brand

Five measurement scales, namely, paired comparison, rank order, magnitude estimation, response scales, and semantic differential, are most widely used during subjective evaluations of automotive sounds [26], [58]. The dimensions used for emotional evaluation of vehicle sounds, such as powerful and pleasant are usually independent dimensions [28]. Therefore, the measurement scale for emotional evaluation should provide an independent measure of each attribute. The measurement scale must also provide a relative rating of the set of sounds used during a particular evaluation experiment. This is because there are numerous vehicle brands and a person without an automotive background is unlikely to know all automotive sounds in existence, thus making comparisons, on an absolute scale, difficult. Therefore, automotive sound quality evaluations are essentially relative ratings of the candidate vehicle sounds [58]. The measurement scale must provide interval level data so that inferential statistics can be performed. If a measurement scale satisfies these necessary criteria then a suitable method can be chosen considering further optional criteria: the shortest duration of evaluation, ease of performing task, and options to measure an experiment's reliability. Otto et al. (1999) discuss the advantages and disadvantages of each method [58]. Based on this information, Table 2.5 summarizes how these methods rate on the discussed criteria.

Out of these methods, numbered response scales and semantic differential are deemed appropriate as only these scales satisfy all the necessary criteria for sound quality evaluations. Namely, they provide an independent measure per attribute, interval level data and have a potential to provide relative rating of sounds. These scales can be improved to provide a relative rating, if the participants are familiarized beforehand with the target vehicle sounds to give them an idea of the variety of sounds used. Then, they should be instructed to make a relative assessment of the sounds based on their exposure to the sound variety.

Table 2.5 An assessment of the measurement scales used for evaluating automotive sounds on subjective attributes

	PC	RO	ME	NRS	SD
Independent measure per attribute	Yes	Yes	Yes	Yes	Yes
Relative rating	Yes	Yes	No	May be	May be
Interval level Data	No	No	Yes	Yes	Yes
Duration of evaluation	5th (longest)	1st (shortest)	2nd	3rd	3rd
Ease of participant task	1st (easiest)	2nd	5th (most difficult)	3rd	3rd
Measures of reliability	Yes	No	No	No	No
Here, PC = Paired Comparison; RO = Rank Order; ME = Magnitude Estimation; NRS= Numbered Response Scale; and SD = Semantic Differential					

If a numbered response scale is used for measuring an attribute, the meaning of the left end of the scale is unclear. Participants may perceive the extreme left end to mean either 'neutral' i.e. not having the attribute being measured, or 'negative' i.e. having the opposite attribute. Semantic differential scales are like numbered response scales but with bipolar adjectives at the opposing ends of the scale. This makes the scale bi-directional where it is clear that the middle point stands for neutrality and the left and right ends are opposing attributes. The inter-participant variability is also less in semantic differential scales [58]. These scales avoid the "pseudoneglect" effect, which is the bias due to attention to the left or right hand side of the scale [75]. They also help reduce the "acquiescence bias", which is the tendency to agree with statements [75].

Scale order and format may also influence responses if they are altered between experimental conditions, as they may potentially confuse participants [75].

The scale format has changed if negative semantics are placed on the left end of the scale, and then on the right end of the scale. By fixing the scale order and format of the semantics for all experimental conditions for a participant, any acquiescence or pseudoneglect bias can be monitored which may otherwise remain unobserved.

Semantic differential scales, however, do not directly give a measure of an experimental method's reliability, which is the ability of obtain the same results if the experimental conditions are repeated. By repeating an experimental condition and then comparing the two data sets, the reliability can be estimated.

2.7. Establishing the Research Question

The literature review shows that methodologies do exist for automotive exterior sound quality evaluations. However, in the context of (H)EV sounds current methodologies need to be integrated or enhanced to evaluate these sounds both for pedestrians' safety and for understanding how these sounds influence pedestrians' impressions on the vehicle brand. Moreover, the current methods do not balance experimental control with an appropriate context and external and ecological validity [9], [10], [33], [34], [37], [38], [59]. The automotive sounds' evaluation tests are fundamentally designed to infer relationship between variables in order to make generic conclusions such as what acoustic or psychoacoustic factors contribute to the enhancement of sound quality [58]. Therefore such tests are primarily experimental in nature [58]. Experimental control is, hence, necessary to ensure accuracy in the results. At the same time, it is important that the evaluation methods have appropriate context and the experimental process approximates the setting of the real world traffic scenarios. These help increase the ecological validity [76] of the evaluation, which should help the listeners within an evaluation test to think, react and respond in the similar way as a pedestrian in a real world traffic scenario. Yet another inherent limitation of an experimental method is that the results may not be externally valid [76], which is that the results are only valid under the controlled environment and may not generalise to the real world. Figure 2.8 summarises the gaps in the knowledge related to evaluating (H)EV exterior sounds.

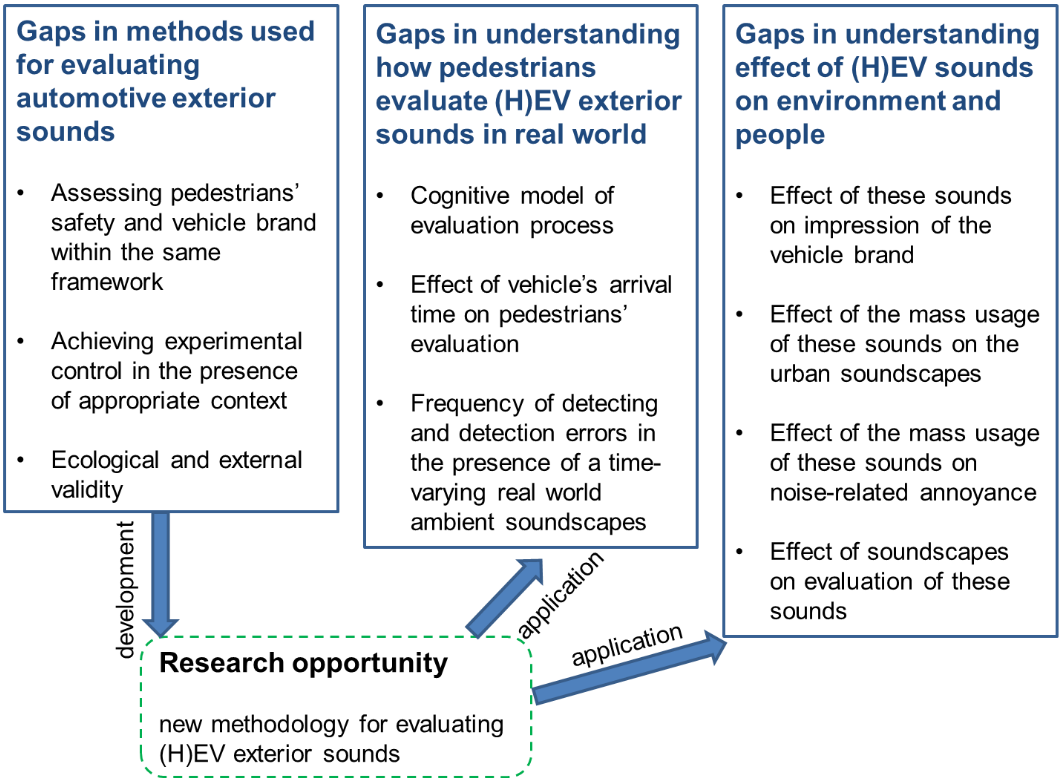


Figure 2.8 Gaps in the knowledge regarding the evaluation of (H)EV exterior sounds based on the findings of the literature review

Therefore, there is a need for a standardised methodology for **"evaluating"** automotive exterior sounds that addresses these gaps in the current methodologies. Furthermore, an understanding is also required about the effects of mass usage of (H)EVs emitting the new sounds on soundscapes and noise-related annoyance. The new evaluation methodology should also help assess and understand these effects.

Currently, there is a lack of knowledge on how pedestrians evaluate (H)EV sounds in the real world for e.g. what cognitive processes they use, how often they detect a vehicle, how often they make errors in detecting a vehicle, and how constantly they evaluate the vehicle brand. As discussed in section 2.6.2.2, it is expected that a pedestrian may have an expectation bias based on the fixed vehicle arrival time during a standard vehicle detection test. Moreover, a pedestrian may also make detection errors in the presence of a real world ambient soundscape. Evidence is required to confirm these hypotheses, which would further help in understanding how pedestrians evaluate (H)EV sounds in the real world. Developing and applying a rigorous and standardised methodology would also help in understanding the evaluation process of the vehicle exterior sounds by pedestrians. This insight would benefit policy makers of the (H)EV sounds, manufacturers, brand managers and transportation researchers.

Therefore, the research question under investigation was:

"How should (H)EV exterior sounds be evaluated?"

To answer the research question in a rigorous and systematic manner the following objectives were set:

I. To formulate an experimental methodology for evaluating (H)EV exterior sounds that includes the criteria of pedestrians' safety and vehicle brand and provides an appropriate evaluation context and experimental control.

II. To examine the fidelity of the experimental setup and the quality of user experience.

III. To assess reliability, control and ecological validity of the experimental methodology when it is applied to a pedestrian interacting with an (H)EV in a traffic scenario critical to pedestrians' safety.

IV. To externally validate the methodology by determining if it accurately predicts pedestrians' evaluation of (H)EV sounds in the real-world.

V. To compare aspects such as the duration, implementation, reliability and control of the methodology to the real-world (on-road) evaluation approach

VI. To produce methodological guidelines for evaluating (H)EV exterior sounds.

The research also aimed to test the following hypothesis to help gain a better understanding of how pedestrians evaluate (H)EV exterior sound in real world.

I. **Hypothesis 1:** Pedestrians' evaluation of vehicle exterior sounds is affected by the change in the vehicle's arrival time.

   a. **Hypothesis 1a:** Pedestrians' rate of detecting a vehicle based on its exterior sounds is affected by the change in the vehicle's arrival time.

   b. **Hypothesis 1b:** Pedestrians' perceptual evaluation of subjective attributes of a vehicle exterior sound quality is affected by the change in the vehicle's arrival time.

II. **Hypothesis 2:** Pedestrians make detection errors in the presence of a real world ambient soundscape.

2.8. Summary

This chapter reviewed the literature and the legislation and identified the major challenges of the (H)EV sounds as ensuring pedestrians' safety, reinforcing the vehicle brand and benefiting soundscapes. A critical review of the current automotive sound quality evaluation methods identified that a new improved methodology is required to evaluate (H)EV sounds that balances experimental control with appropriate context, ecological and external validity. Based on these gaps, research question, objectives and hypotheses for this project were set.

Chapter 3: Research Methodology

3.1. Introduction

Chapter 2 discussed the research question "How should (H)EV exterior sounds be evaluated?" This chapter describes the research methods and approach used to address this question. A brief description of the study design is also presented but the details for individual studies are presented in chapters 4, 5 and 6. Further, this chapter summarises the learning gained from the literature review in chapter 2. Based on which, the chapter proposes an experimental methodology, namely, "**methodology-v1**" (version 1 of the methodology) for evaluating (H)EV exterior sounds. This is followed by the description of the study sample, sampling strategy, and the experimental setup. The chapter closes with a discussion of the ethical issues and considerations of this research.

3.2. Research Methods and Approach

3.2.1. Framework for research

The research aims at developing appropriate methods for evaluating (H)EV exterior sounds. In the context of this research, "**evaluation**" of (H)EV exterior sounds refers to the detection as well as the perceptual evaluation of the subjective sound quality attributes ([26], [58]) of the (H)EV. Since such evaluation methods would essentially involve listening tests with people [26], [58], the research is closely associated with fundamentals of experimental design and cognitive psychology. Thus, the research fits within the disciplines of automotive sound quality, auditory detection tests, design of experiments in psychology and cognitive psychology.

Vehicle legislations will play the most influential role in determining the acoustic specifications, operational criteria and pedestrian's perceptual requirements of the additional sounds for (H)EVs. Moreover, as discussed in chapter 2 the manufacturers have their expectations and requirements that these sounds reinforce the vehicle brand. Therefore, the overall research framework (see Figure 3.1) [77] used information from the following sources to come up with methodological guidelines for evaluating (H)EV sounds:

I. **Literature**
   a. Automotive sound quality
   b. Auditory detection tests
   c. Design of experiments in psychology
   d. Cognitive psychology

II. **Legislation** governing the (H)EV sounds

III. Automotive **Industry** to understand (H)EV manufacturers' requirements and expectations from these sounds

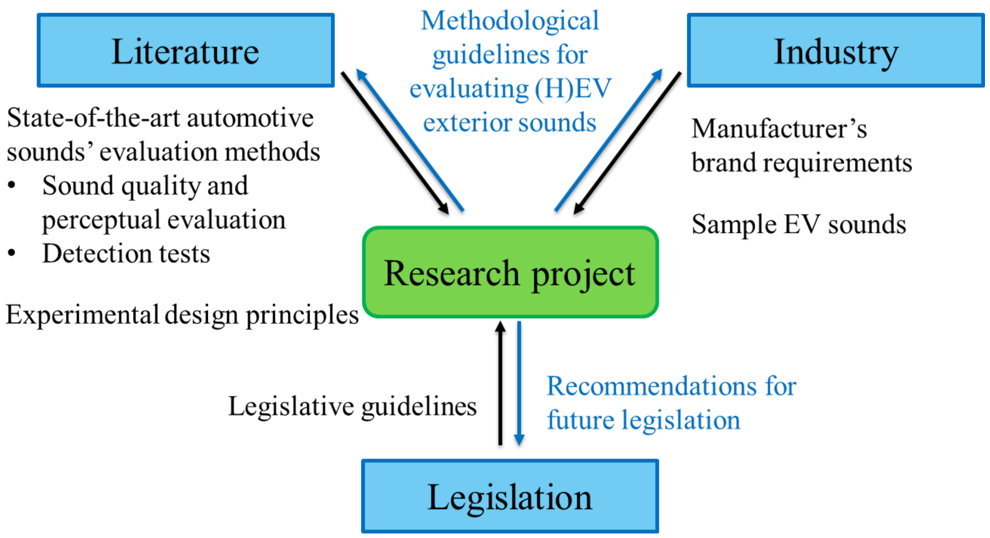


Figure 3.1 Framework for the research project

3.2.2. Stages of research

Based on the research framework, chapter 2 reviewed the state-of-the-art automotive sound quality evaluation approaches in the context of experimental design and cognitive psychology. This led to the formulation of an initial methodology for evaluating (H)EV exterior sounds, namely methodology-v1 (see 3.3.2). The rigorous literature review, as well as a consideration of the concerned legislation and manufacturer's requirement ensured that the methodology-v1 had construct and content validity.

Next, an iterative process tested the application of the methodology and validated the methodology through a series of experimental studies. Automotive sounds' evaluation tests are fundamentally designed to infer relationship between variables such as what acoustic or psychoacoustic factors contribute to the enhancement of sound quality [58]. Therefore such tests are primarily experimental in nature [58]. For this reason, the research was primarily quantitative in nature and used experimental methods in psychology.

Chapter 2 discusses the limitations of current methods such as the lack of ecological and external validity while maintaining experimental control. The proposed methodology aims at overcoming these limitations. Therefore, the methodology was validated using the standard experiment criteria of reliability [78] (to assess experimental control) and ecological and external validity [76] (to assess how effectively these methods generalise to real-world traffic scenarios). Figure 3.2 shows the flowchart of the stages followed in this research.

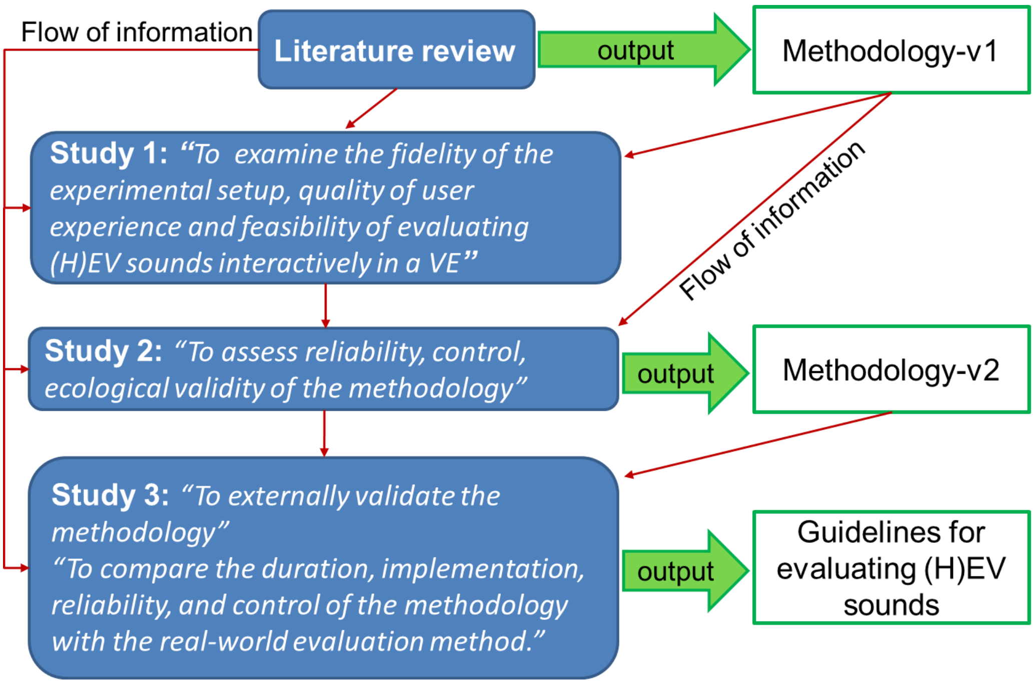


Figure 3.2 The stages of the research

3.2.3. Study design

This research involves various experimental studies to apply, test and validate the methodology. In general, there are two types of experimental design — independent group (between-subjects) design and repeated measures (within-subjects) design [79]. A **repeated-measures design** was selected for all studies because this design eliminated the requirement of having equivalent groups [79]; a problem that is common in independent group design. Secondly, compared to independent group design, repeated measures design required fewer participants to achieve the same statistical power [79]. Moreover, repeated-measures design is always a favourite among perception researchers. This is because such research requires extensive lab set-up and preparation of the different stimuli, and much less time to expose participants to different stimuli one after another [79].

3.3. Proposal of a methodology for evaluating (H)EV exterior sounds

3.3.1. Learnings from literature review

A review of the current methods and approaches revealed a methodology is required that integrates the evaluation criteria of pedestrians' safety with vehicle brand. At the same time, it achieves a balance between experimental control with appropriate context, external and ecological validity. Simulating VE has the potential to provide an appropriate visual and auditory context. Simultaneously, the researcher can fully control the experimental variables, such as ambient soundscape, traffic, visual scenario, and target vehicle's direction and its arrival time. Thus, VE simulation can potentially provide experimental control with context.

It has also been argued that participants may falsely detect a target vehicle by confusing it with spikes in some transient real-world ambient sounds. Giving the participants an option to record the detection time more than once would help monitor if and how participants make detection error. It has also been argued randomly varying a vehicle's arrival time across the experimental conditions makes pedestrian-vehicle interactions more realistic (see 2.6.2.2). Therefore, the methodology should incorporate all these elements while evaluating (H)EV sounds.

3.3.2. Methodology-v1

The methodology-v1 proposes evaluating (H)EV exterior sounds through an experimental approach that assesses these sounds:

I. To ensure pedestrians' safety using the following measures:
   a. How quickly or slowly is the approach of an (H)EV detected by the pedestrians using its exterior sounds ("**detection rate**")?

II. To ensure the sounds reinforce the vehicle brand image using the following measures:
   a. How "**powerful**" is the (H)EV perceived based on its exterior sounds?
   b. How "**pleasant**" is the (H)EV perceived based on its exterior sounds?

Powerful and pleasant are used as they are validated (see 2.6.3.2) and amongst the most widely used perceptual dimensions of automotive sound quality [28], [56], [57]. The methodology-v1 also proposes the following experimental guidelines for evaluating (H)EV exterior sounds:

I. Use an **immersive virtual environment(s)** (VEs) to provide the context of a real life pedestrian-vehicle interaction(s) through
   a. Traffic scenario(s) that are critical to pedestrians' safety (e.g. electric car moving at low speeds in parking lots, T-junctions, and crossroads)
   b. Ambient sounds that represent real life urban environments

II. The methodology should follow the principles of experimental design:

a. Randomizing the order of presentation of the experimental conditions to control for sequence effects.

b. Using valid and reliable scales such as semantic differential, for subjective evaluation of sounds.

Additionally, based on the argument in section 2.6.2.2 and to test the research hypotheses following guidelines were also included:

III. Detection time measurement method should have options for recording many instances of detections.

IV. The target (H)EV's direction of approach and time of arrival at the pedestrian's position from the beginning of an experimental condition may be randomly varied throughout the experiment.

Figure 3.3 presents a flowchart that summarises the key aspects of the methodology-v1.

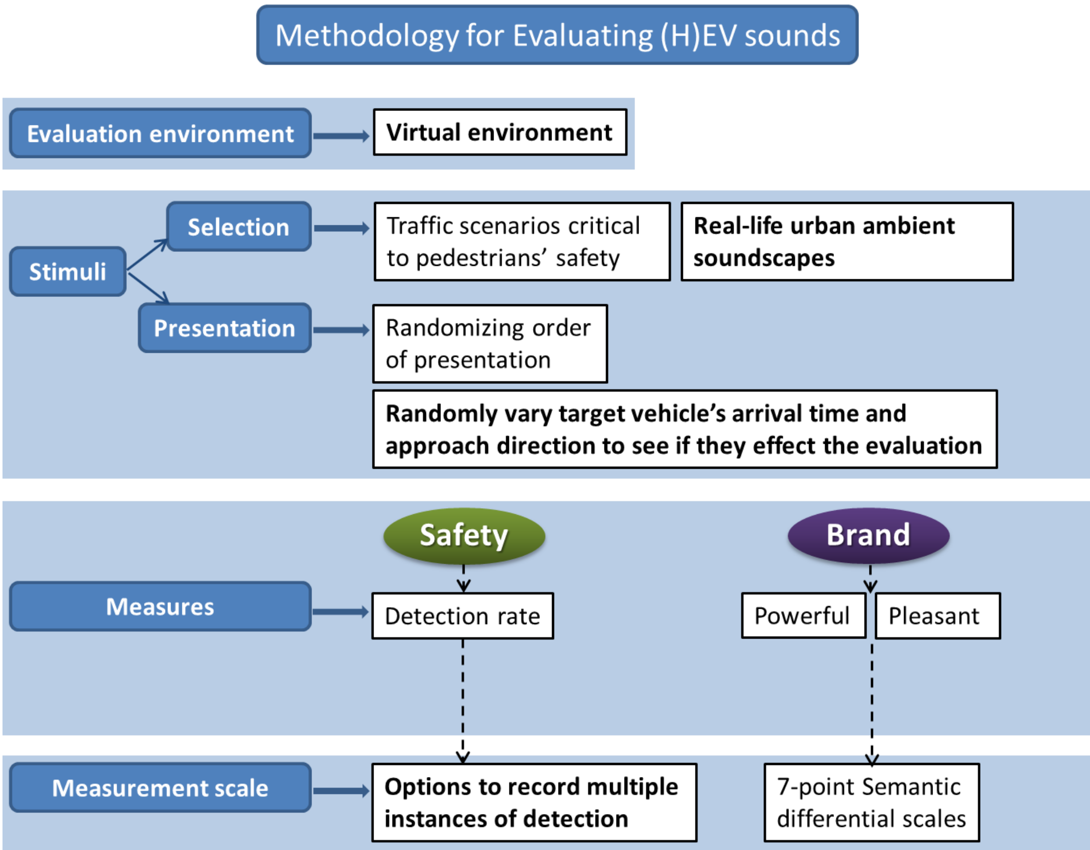


Figure 3.3 Methodology-v1.
Here, bold writings denote the novel approach not found in existing methodologies

3.4. Study Sample

3.4.1. Study population

The studies involved evaluation of the vehicle sounds from the perspective of an adult pedestrian. To select participants in an un-biased random way the research was open to anyone that can represent an adult pedestrian. People below 18 years of age and above 55 years were not included because of ethical concerns. Thus, the study population constituted the members of general public within the age group of 18 to 55 years. Since, the “absolute threshold of hearing” (minimum SPL of a pure tone that an average human ear with normal hearing can hear with no other sound present [11]) changes as people reach 60 years or above [11]. Therefore, selecting people within 18 to 55 years age group helped ensure that the study population has a similar threshold of hearing. Further, participants had to evaluate electric cars based on sounds and/or visuals; therefore, a participant was not allowed to have any hearing impairment and any uncorrected visual impairment. Based on the ethical guidelines of the University of Warwick (see 3.5.5) unfit or sick participants and pregnant women were excluded from the recruitment process. Figure 3.4 shows the criteria of selecting the study population:

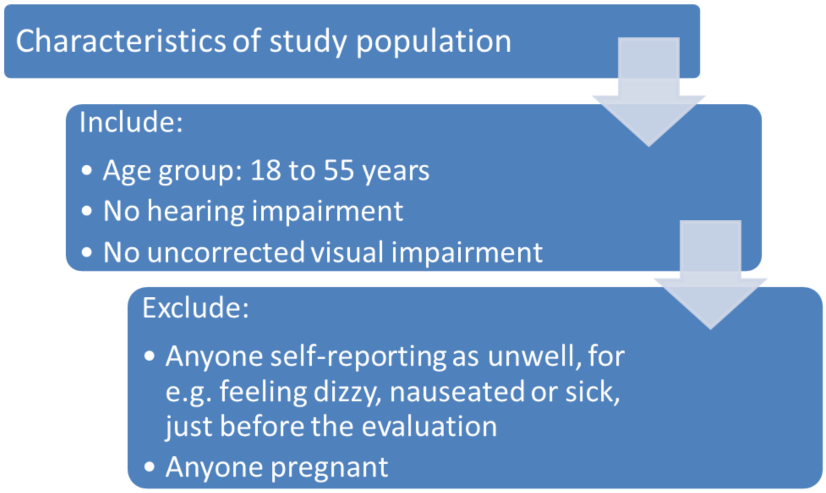


Figure 3.4 Characteristics of the study population

3.4.2. Sampling strategy

Since the research interest is on adult pedestrians from the general public instead of members of any particular special interest group, convenience sampling was adopted. Convenience sampling is a qualitative, non-probabilistic sampling technique that does not target any specific group of participants but recruits them based on their accessibility [80]. Based on this sampling design, participants were primarily recruited from among the students and staff members at the University of Warwick because this facilitated accessibility of the participants to the researcher as well as accessibility of the experiment location to the participants. However, the participation was also open to the general public provided they qualified to be within the study population (see Figure 3.4).

The administration staffs of WMG were approached to email an invitation letter for participation to the staff and students contacts at WMG, and the school of Engineering and its referrals. In order to reach a broader audience, beyond the Engineering background, the research was promoted by displaying posters and flyers at the University areas accessible to general public such as Warwick Arts Centre, Library, and Student Union building. The letter and the poster had researcher's contact information and people interested were asked to contact the principal researcher. Appendix 1 contains the invitation letter and the poster prepared for the recruitment process. Those who replied expressing interest in participation were sent an information sheet, and consent form (Appendix 1). A convenient time slot was booked for every participant through subsequent email. Participants were requested to bring the signed consent form either when they came for the experiment or sign it just before the experiment.

3.4.3. Sample size

The sample size requirement was directly related to the selected method and the objective of each particular study. Study 1 was a descriptive experimental study that did not require any inferential statistics for hypothesis testing. Therefore, the sample size for study 1 was taken as the minimum number of participants required to achieve a theoretical saturation point which is defined as a point after which no additional insight to the inquiry can be gained [80]. In the context of study 1, the theoretical saturation meant a point when participants' comments started reappearing, and successive participants added no new information or feedback.

Studies 2 and 3 were inferential experimental studies that used Analysis of Variance (ANOVA) design. The sample size for these studies was pre-determined using Software G*Power 3.1.7 [81], so that the sample size met the minimum number of participants required for a minimum statistical power of 0.8 [82] and type I error probability, $\alpha = 0.05$, with a medium effect size, $f = 0.25$ [82].

3.5. Experiment Setup

3.5.1. Equipment: Exterior Sound Simulator

Exterior Sound Simulator (ESS) is a software tool by Brüel and Kjær that can synthesize the visual and audio stimuli of an EV moving in a town and carrying out different manoeuvres, as it would be seen and heard by a pedestrian [74]. ESS is an extended version of 'NVH vehicle simulator' [73]. ESS is a novel and one-of-a-kind software tool that can simulate a VE from a pedestrian's perspective. It has an in-built UK town model namely, "Hitchin town". This town model includes various places where a pedestrian-vehicle interaction is likely, such as: car parks, crossroads, junctions with and without traffic lights, bus stops, streets, residential roads and market areas [10], [44]. Figure 3.5 shows the various visual scenarios available within ESS.

ESS uses "source decomposition technique" [83] that facilitates the researcher to decompose a vehicle's total sound into source based component sounds (e.g. engine harmonics, tire sound, wind sound, and alerting sounds from sound emitting devices). These component sounds are stored as a vehicle's sound model. ESS also allows a researcher to create trajectories of a pedestrian's and a vehicle's manoeuvre in any chosen location of the virtual town. The ESS software takes the sound model and the manoeuvre data as input to synthesize the visual and the sounds that the pedestrian will experience in the corresponding scenario. Detailed explanation of simulation algorithms are mentioned by its developers in a number of research articles such as [73], [74], [83].

Figure 3.5 Examples of visual scenarios available in Hitchin town model in ESS.

3.5.2. Laboratory: Soundroom

A soundroom is a closed semi-anechoic room located at the International Digital Laboratory at the University of Warwick. Figure 3.6 shows the schematic of the soundroom. It has eight floor speakers arranged in a regular octagon and three adjoining screens outside the circle of the floor speakers.

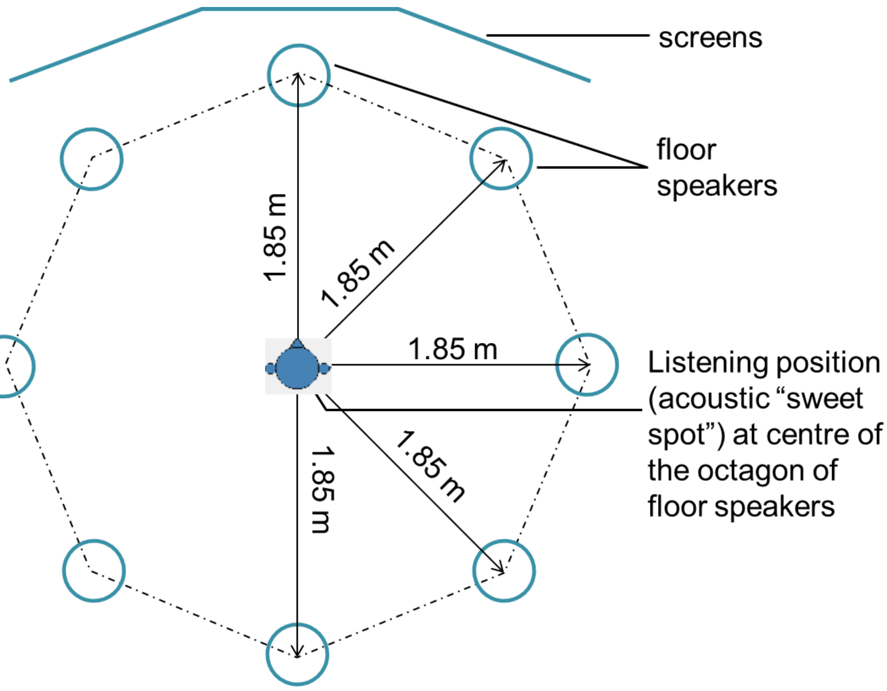


Figure 3.6 Schematic of the soundroom. Here, blue lines show the equipment layout.

3.5.3. Evaluation environment for VE experiments

Experiments were conducted by simulating a virtual town environment presented through ESS inside the soundroom. The participant was seated on a chair at the centre of the floor speaker octagon so that (s)he faced the soundroom screens. The visuals synthesized by ESS were projected on these screens over a display size of 1.6 m X 2.13 m per screen, an aspect ratio of 4:3 per screen, and at a resolution of 1280X1024 pixels per screen. The brightness measured at the screens of the projected visuals was 130 cd/m^2 (candela per square metre) and dynamic contrast ratio (dynamic range) was 400:1.

Sounds synthesized by ESS were played through the floor speakers. The sounds were calibrated at the participant's sitting position. To achieve this, the ESS audio output was connected to the speakers using the standard technique of virtual sound source positioning using vector base amplitude panning [84] to create a two-dimensional sound field. To calibrate the SPL of the sounds, the same chair, as used during experiments, was placed at the centre of the floor speaker octagon. A team member connected the ESS audio output to each speaker one at a time and played an 80 dB sine wave from the simulator’s pure tone generator. Another team member sat on the chair and binaurally recorded the sounds produced at his ears using Brüel & Kjær Sonoscout NVH Recorder - Type 3663 (Figure 3.7). The speaker volume gain was adjusted to match the sound level produced at the ear’s position. Later, the ESS audio output was set to all speakers and the total sound level produced at the ear’s position was checked. ESS has option to input the eye height for the visuals, which was set as 1.6 metres for all experiments. So, every participant saw the visuals as seen by an upright pedestrian with eye height 1.6 metres. Participants therefore experienced vehicles as if they were standing at a real-world traffic scenario. This soundroom-ESS setup was the evaluation environment for all VE experiments conducted as part of this research.

Figure 3.7 Brüel & Kjær Sonoscout NVH Recorder - Type 3663.

3.5.4. Equipment setup for real-world experiments

Real-world experiments were designed so that participants could listen to and evaluate the target EV sounds while being a pedestrian in a traffic scenario in a real world location chosen for the study (see 3.5.5). For these experiments, the target EV was an electric car from a current manufacturer that was fitted with speakers on its front exterior positioned below the windscreen (Figure 3.8). The EV was required to emit different sounds as desired SPLs and also be capable of varying the sound character such as its frequency modulation (or pitch) with vehicle speed in order to comply with the legislation [21], [24], [25]. This was achieved using VSound software developed by Brüel and Kjær. The driver could select various sound profiles (5 to 12 s wave files) from a laptop containing VSound (Figure 3.9). VSound took the speed and throttle inputs from the EV and produced the output sound as a continuous emission of the selected sound profile in a speed range of 0 to 20 mph (≈ 0 to 32 kph) at the desired sound level (dB(A)$_{eq}$) at the external speakers. The frequency modulation and pitch of the output sound varied linearly with vehicle speed.

Figure 3.8 The target EV for the real-world experiment.

Figure 3.9 The sound delivery setup inside the target EV in the real-world experiment.

3.5.5. Analysis software tools

The software IBM SPSS Statistics 21 was used for all inferential statistics in this research project. All other processing was done using Microsoft Office 2010.

3.6. Ethical Considerations

The research involved human participants, thus the research protocol was reviewed and approved by the Biomedical and Scientific Research Ethics Committee (BSREC) at the University of Warwick. Appendix 2 shows the ethical approval letter of this research. The ethical considerations are listed below.

The BSREC recommendations limited the auditory stimuli for all experiments to be between 30 to 80 dB, to avoid any possibility of noise induced hearing loss [85]. Additionally, the BSREC also approved the visual stimuli. Only participants who reported as feeling well with no symptoms of dizziness, nausea, or sickness just before the evaluation were allowed to do the experiment. This was done to reduce chances of participants getting sick due to exposure to simulations. For the same reasons, vulnerable people such as pregnant women, elderly and children were not recruited for participation. Moreover, participants had a choice to withdraw at any point during the evaluation. Sitting arrangement, water and assistance was available outside the lab if any participant would fall sick or tired during or after the experiment. Thankfully, such incidents never occurred during this research.

Pilot sessions were held before opening any study to the public. During real-world evaluations in study 3, every care was taken to reduce any risks to participants and experimenters. Participants always stood on the road pavement and trained drivers were used for driving the target car. The car's speed was always maintained below 20 mph (32 kph). The real-world evaluations were conducted at the Lakeside residences at the University of Warwick campus. This area was suggested by the University's estate and security staff as it provided a secured location only accessible to University approved vehicles, thus little traffic. The experiments were conducted at off-peak times to avoid traffic and other pedestrians. The University's security staff was readily available to contact in case of emergencies.

All information collected from participants during this research is kept strictly confidential. The data is being made anonymous right from the analysis stage. For this, results from different participants are distinguished using a unique participant ID. Thus, any published data cannot be traced back to the participant. The research data has been stored and managed in accordance with the University of Warwick Research Data Management Policy. It has been stored in a coded form through regular backup on secure University servers. It will be available for ten years from the date of the studies after which it will be destroyed.

3.7. Summary

This chapter has described the methods used within this research project. The research framework uses literature on automotive sound quality, legislation and manufacturing industry as the three information sources. This helped in proposing a new methodology. The research question is answered through a series of experimental studies that test and validate the proposed methodology. These studies use repeated measures design to eliminate the requirement of having equivalent groups and require fewer number of participants compared to alternative designs. An Exterior Sound Simulator presented a VE from a pedestrian's perspective within a semi-anechoic soundroom laboratory at WMG. This is the evaluation environment used for all experimental studies conducted as part of this research.

Chapter 4: Equipment Fidelity and User Experience

4.1. Introduction

Chapter 3 described ESS as a software tool that is part of the NVH vehicle simulator [73] used in this research project for presenting VEs from a pedestrian's perspective. Since the proposed experimental methodology is developed around this simulator and soundroom, ESS is being used as the setup in all of the experimental studies. Firstly, therefore, it was important to examine the fidelity of this setup, or in other words, the effectiveness of the setup in simulating a real world traffic environment. It was also necessary to assess the quality of experience of the participants when exposed to the VE. ESS offers two modes of evaluating vehicle sounds:

I. "**Interactive mode**" / "**Free driving**": In this mode a participant is able to navigate freely as a pedestrian in the VE by giving inputs of speed, acceleration, and direction from a gamepad linked to the simulator. The ESS synthesised auditory and visual stimuli as heard and seen by the participant is generated in real time in response to the user inputs via the gamepad. The current NVH simulator capability however only allows pedestrian interactivity and not pedestrian-driver interactivity. This means that in this mode, the manoeuvre(s) of the target car and other vehicles in the traffic remain fixed as pre-defined by the researcher.

II. "**Non-interactive mode**" / "**Fixed exterior**": In this mode, the researcher predefines both pedestrian and vehicle(s) manoeuvre. Thus, the participant experiences himself/herself as a pedestrian moving in the VE and interacting with the vehicle(s) in a pre-defined manner. The participant is exposed to the fixed visual and auditory stimuli corresponding to his/her manoeuvre.

There is very limited literature supporting the use of such "interactive mode" on sound quality evaluations or on product evaluations in general. Research is also lacking on how interactive mode may affect vehicle exterior sound quality evaluation. Nevertheless, the interactive mode functionality within this simulator seems promising, so it was decided to explore this functionality and assess its appropriateness for conducting (H)EV sound evaluations. This chapter describes the findings and implications of an exploratory study conducted to explore the fidelity of the experimental setup, the quality of its user experience and feasibility of the interactive mode of evaluation.

4.2. Study 1: Objectives

The study was designed to achieve the following objectives:

I. To examine the fidelity of the experimental setup

II. To assess the quality of user experience

III. To explore the feasibility of the interactive mode of evaluating (H)EV exterior sounds

4.3. Study 1: Selection of Measures

4.3.1. Simulation fidelity and effectiveness of VE

ESS was installed in the soundroom laboratory within WMG (see 3.5.3). This soundroom-ESS set-up has been used throughout this research project to present a VE of a typical UK town that is supposed to represent real life urban traffic situations. This simulator is the primary research instrument in this project therefore, it was important to check the fidelity of the simulation.

Literature defines "simulation fidelity" as the extent to which the appearance and behaviour of the simulator⁄ simulation match the appearance and behaviour of the simulated system [86]. In the context of a VE setup is can be defined as the extent to which the VE emulates the real world [87]. Fidelity of a simulator, the effectiveness of the VE, quality of experience of its users, as well as their enhanced task performance in a VE is often directly linked to a higher level of "**presence**" reported/experienced by its users upon exposure to the VE [62]–[64]. In the context of this research, a higher level of presence would imply a greater degree to which its users experience feeling 'present' and 'immersed' in a real-life traffic scenario [62]–[64]. Therefore, to test the fidelity and effectiveness of the experimental setup and the quality of experience of its participants, this study measured the level of presence experienced by the participants upon exposure to the VE.

Presence, in general, is defined as the subjective experience of being in one place or environment, even when one is physically situated in another [63]. From the literature on immersive VR and VE, 'presence' can be summarised as: "experiencing the computer-generated environment rather than the actual physical locale" or; the "sense of 'being there'" in the VE or in the place depicted by the VR rather than in the real physical place where the participant's body is actually located" [63], [64].

The **Presence Questionnaire** (**PQ**) by Witmer and Singer (1998) [63] is the standard questionnaire for measuring the level of presence experienced in a VE. It has been extensively validated, tested and widely used to check fidelity of many VE and VR systems. Therefore, it enables comparisons with other studies and was chosen for this study to measure the level of presence experienced by the participants of the VE used in this research. Appendix 3.1 shows the items of the original PQ by Witmer and Singer (1998) [63] and the factors and subscales associated with each item.

4.3.2. Quality of experience of participants within the VE

The VE presented through soundroom-ESS setup used in this research is new to the field of automotive sound quality evaluations. It is equally important to assess the quality of experiences of the participants upon exposure to this VE. Previous research shows that users in a VE may experience a form of sickness, similar to motion sickness, often referred to as **"simulator sickness"** [88]–[96]. Simulator sickness has been identified as a form of motion sickness experienced by the users of systems that present optical depictions of inertial motion, such as flight and driving simulators, and VEs and VRs that simulate motion [88]–[96].

Simulator sickness is generally a less severe and less frequent form than actual motion sickness and people suffering from it exhibit only fewer symptoms compared to actual motion sickness [97], [98]. However, the effectiveness of simulation and VE systems, and their acceptance by the users, can be severely limited if they produce simulator sickness symptoms. Moreover, in this research simulator sickness experienced by the participants when exposed to the VE setup may reduce their task performance during evaluations, which may then affect the outcomes of the evaluation experiments. Therefore, it was important to measure and identify the degree of simulator sickness experienced by participants when exposed to the experimental setup used in this research.

Simulator Sickness Questionnaire (**SSQ**) developed by Kennedy et al. [98] is an established method for measuring simulator sickness. It has undergone extensive validation and testing, and it is widely used in laboratory and field studies involving VE/VR simulations [95], [96], [99]. Therefore, it enables comparisons with other studies. Due to these reasons, SSQ was chosen to measure the degree of simulator sickness experienced by the participants upon exposure to the VE-system used in this research. SSQ contains 16 symptoms to measure the level of simulator sickness and “nausea”, “oculomotor” and “disorientation” are the three factors or subscales underlying these symptoms [98] (See Appendix 3.2).

4.3.3. Feasibility of interactive evaluations

Interactive mode, where a participant can freely navigate the VE to interact and evaluate the vehicle as (s)he would like (see section 4.1), has not been used before for vehicle exterior sound quality evaluations. However, previous studies on the interactive mode of evaluating automotive interior sounds using the NVH Simulator show that the NVH engineers and key decisions makers from contemporary automotive manufacturers consider interactivity as an enhanced and useful feature of the sound quality evaluation process [72], [100]. A study by Giudice et al. (2007) shows that driving strategies adopted when evaluating vehicle interior sounds using interactive mode of the NVH simulator can help gain a better understanding of how customers evaluate sounds of a vehicle [101]. Thus, using interactive mode may improve the simulator's evaluation experiments which may lead to more effective and efficient decision making during the vehicle development process [101]. It is reasonable to assume that interactive evaluation of vehicle exterior sounds may also benefit the vehicle NVH process.

Therefore, this study explored the interactive mode of conducting vehicle exterior sound evaluations, checking its feasibility, usefulness, as well as any disadvantages of using this mode. This was done using the following measures:

I. **Participants' repeatability:** The simulator offers the option of recording the time history of the pedestrian's manoeuvre in the VE in the form of fixed performance model files. These files were stored and compared to see how repeatable participants were in performing the task.

II. **Participants' feedback**: An open-ended feedback on the various aspects of the evaluation, such as the evaluation environment, method of data collection, and choice of measures, was collected.

III. **Level of difficulty/ease of performing evaluations:** This was assessed by the researcher's close observation of the participants during evaluations that helped identify issues, difficulties or convenience/inconvenience they face whilst using the interactive mode. During the experiment, every participant was asked to perform the same specific task (see section 4.4.4) and allowed to have a minimum one and maximum two trials per visual scenario to get accustomed to using the gamepad (see section 4.4.7). As an objective measure, the number of trainings demanded by the participants for using gamepad was noted. The duration of the experiment was also noted.

4.4. Study 1: Experiments

4.4.1. Participants

The participants were recruited from the study population set for this research (see 3.4.1). The data was collected from 8 participants as theoretical saturation [80] was obtained from the feedback on participant 7 and 8. The participants were 4 males, 4 females, mean age = 33.3 years, comprising faculty, staff, and students of the University of Warwick. Table 4.1 shows the profile of the participants of this study.

Table 4.1 Profile of participants used in study 1.

Participant ID	Age	Gender	Previous experience of VE	Susceptibility to motion sickness
1	48	Male	Yes	Low
2	33	Female	Yes	Low
3	27.5	Male	Yes	Low
4	31.5	Female	Yes	Moderate
5	41	Female	No	High
6	34	Male	No	Low
7	25.5	Male	No	High
8	26	Female	No	Low

4.4.2. Evaluation environment

All evaluations were conducted in the Soundroom-ESS set-up (see 3.5.3). Figure 4.1 shows the evaluation environment in study 1.

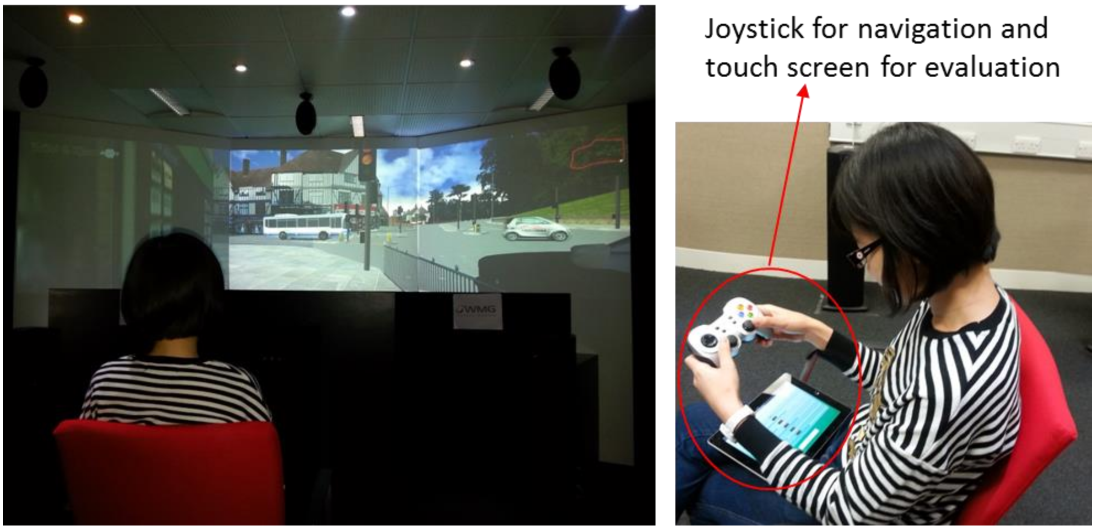


Figure 4.1 Evaluation environment in study 1.

4.4.3. Stimuli

The literature review has identified critical scenarios of pedestrian-vehicle interactions (see 2.2.3). Hence, in line with previous research the selection of visual and auditory stimuli for this study was done to include these scenarios, as they are critical to pedestrians' safety and require the use of additional sounds from EVs.

4.4.3.1. Visual stimuli:

Scenario 1A: Car park: The participant was exposed to a car park adjoining a two-lane straight road. Figure 4.2 shows the layout of the scenario. The target car was one of the parked cars and reversed back from the car park at an acceleration of 0.5 m/s^2 .

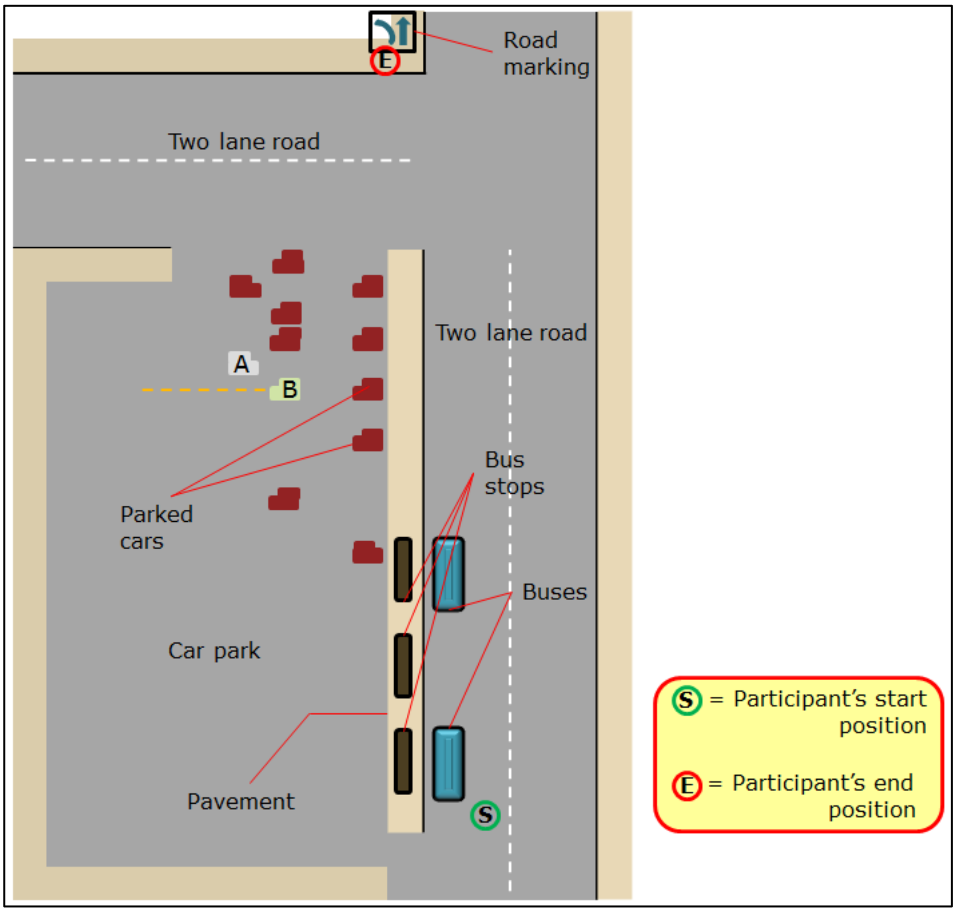


Figure 4.2 Layout of Car park. Car B denotes the target car and yellow dotted lines denote the target car's travel path.

Scenario 1B: Car park: This scenario was same as 1A except that the target car started moving forward from stop with 0.5 m/s^2 acceleration.

Scenario 2A: Crossroad with traffic lights: The participant was exposed to a straight road that ended in a crossroad junction with traffic lights. Figure 4.3 shows the layout of the place. The target car approached the junction from the perpendicular road at 8 mph (12.9 kph) and stopped at the traffic light as it turned red. It started from stop accelerating at 1 m/s^2 when the traffic lights went green. It turned into the road parallel to pedestrian's intended path and moved at a constant speed after reaching 15 mph (24.1 kph).

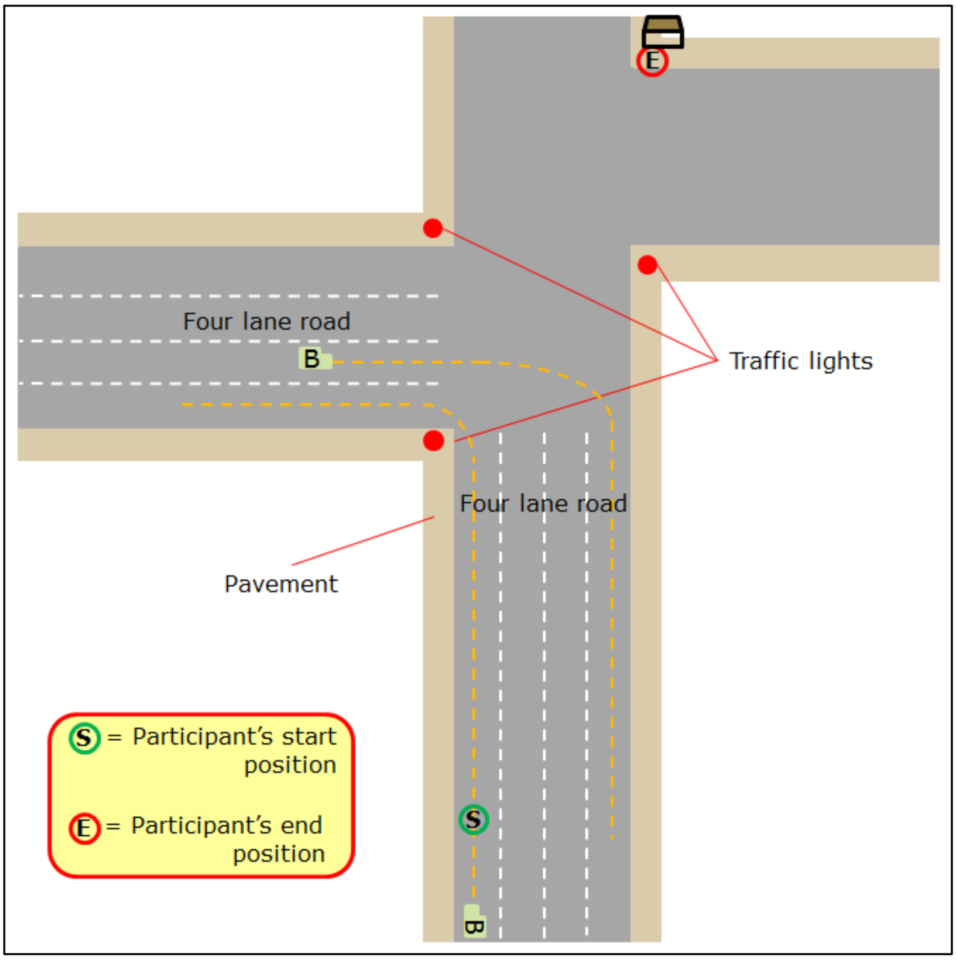


Figure 4.3 Layout of the crossroad junction with traffic lights. Car B denotes the target car and yellow dotted lines denote the target car's travel path.

Scenario 2B: Crossroad with traffic lights: The scenario was same as 2A. However, now the target car ran on the road parallel to pedestrian's intended path at 8 mph (12.9 kph), approached and stopped at the traffic lights until it turned green. Then it accelerated at 1 m/s^2 while turning into the perpendicular road and moved at a constant speed after reaching 15 mph (24.1 kph).

Scenario 3A: T-junction with no traffic lights: The participant was exposed to a two-lane street road that ended into a T-junction with no traffic lights. Figure 4.4 shows the layout of the place. The target car approached the T-junction while running parallel on the street road at 15 mph (24.1 kph) and then decelerating at 1 m/s^2 as it turned towards left on reaching the junction. Then it continued to move on the perpendicular road after attaining speed of 8 mph (12.9 kph).

Scenario 3B: T-junction with no traffic lights: The scenario was same as 3A but now the target car moved at a constant speed of 8 mph (12.9 kph) in the perpendicular road, approaching the junction from the pedestrian's left hand side.

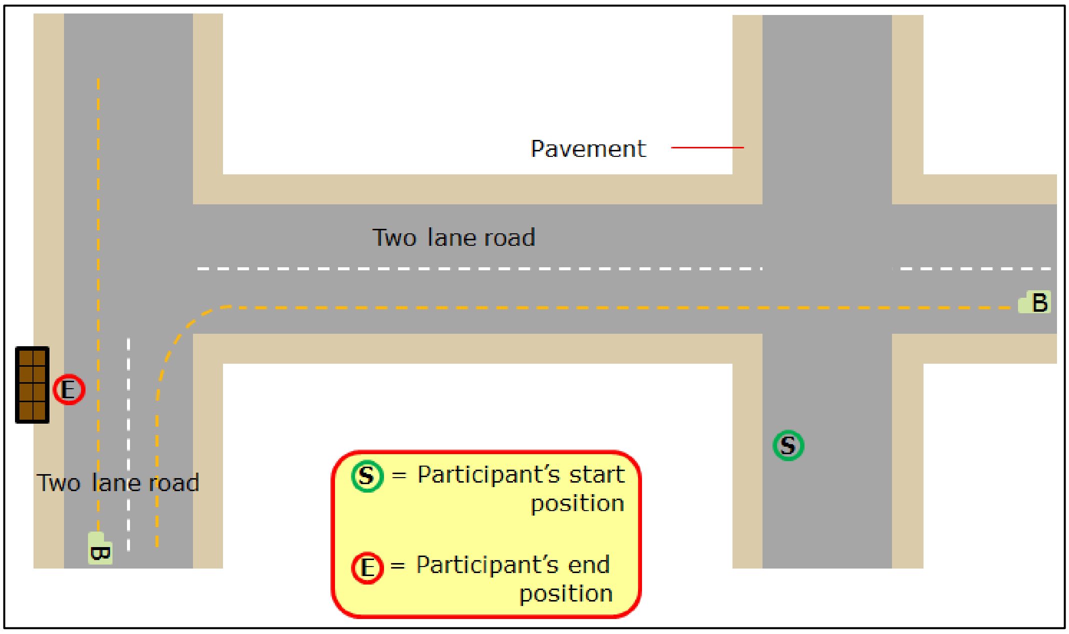


Figure 4.4 Layout of T-junction with traffic lights. Car B denotes the target car and yellow dotted lines denote the target car's travel path.

4.4.3.2. Auditory stimuli:

Two sounds were used for the target car, sound 1 for scenario 1A, 2A and 3A, and sound 2 for scenario 1B, 2B and 3B respectively. Two ambient sounds were used, ambience 1 for scenario 1A, 2A and 3A, and ambience 2 for scenario 1B, 2B and 3B respectively. Table 4.2 and Table 4.3 describe the subjective content and the key metrics respectively of the sounds used in this study.

Table 4.2 Subjective description of the sounds used in study 1

Sound ID	Description
Sound 1	A twin peak signal composed of sinusoidal and irregular waves with peaks frequency at 650 Hz and 2500 Hz and a dip at 1000kHz [37]
Sound 2	Pure tones signals looped to sound like a spaceship
Ambience 1	An 18s binaural recording made in a quiet car park
Ambience 2	An 8s binaural recording in a quiet park in a city

Table 4.3 Key psychoacoustic metrics of sounds used in study 1

Sound	SPL (dB(A))	Loudness (sones)	Sharpness (acum)	Roughness (asper)
Sound 1	55	5.8	1.46	0.46
Sound 2	60	8.8	1.19	0.50
Ambience 1	42	4.4	0.99	0.15
Ambience 2	41	4.4	0.94	0.15

4.4.4. Participant's task

The participants were given instructions to perform specific tasks in each visual scenario. This was done to mimic a more realistic scenario where a pedestrian interacts with the target car while performing some mundane tasks such as crossing a signal to reach his/her house, or walking through a car park to get to his/her car, etc. These instructions also ensured that the participants would follow similar paths and could interact with the target car on their way.

For Scenario 1A and 1B, participant was given the following instructions:

"Go to the car park to reach for your shiny silver car (car A in figure 4.2). After this, reach for the road marking sign on the other side of the road (position E, figure 4.2)".

For Scenario 2A and 2B, participant was given the following instructions:

"Go to the traffic signals, cross the signal junction to reach the house on the opposite side of the traffic signal junction (position E, figure 4.3)".

For Scenario 3A and 3B, participant was given the following instructions:

"Turn left from the first junction, then go straight and again turn left on the next junction to reach the Cannon house on the opposite side of the road (position E, figure 4.4)".

In every scenario participant after navigating and interacting with the target car was asked to rate the target car's sounds on the following 7-point bi-polar semantic scales:

I. not detectable – detectable
II. weak – powerful
III. unpleasant – pleasant

These semantics were chosen in accordance with methodology-v1 proposed in chapter 3 (see section 3.3.2) and were evaluated on an electronic touch screen tablet with the ESS-linked evaluation interface (Figure 4.1 and section 5.3.4). Since this study was exploratory and had aims different from evaluating vehicle sounds, the participant's rating on these semantics were not used for analysis.

4.4.5. Measures

4.4.5.1. Pre-exposure questionnaire:

A pre-exposure questionnaire collected data from participants before they were exposed to the VE set-up (see Appendix 3.4). Research shows that the degree of simulator sickness symptoms and the level of presence experienced by a participant are affected by the participant related variables such as age, gender, previous exposure to VE, and individual differences in sickness susceptibility, concentration, and tendency of becoming easily involved or immersed in an environment [63], [88], [92], [99], [102]. Thus, it was important to collect these data to understand this bias. Moreover, it was important to know the experience of participants with using gamepads as it would directly affect their task performance.

Therefore, the pre-exposure questionnaire had questions about participants' **age**, **gender** and **whether they had experienced a VE before**. The **Immersive Tendency Questionnaire** (**ITQ**) and **Motion Sickness Susceptibility Questionnaire** (**MSSQ**) are established and validated measures to administer an individual's tendency to become involved or immersed in a VE, and his/her susceptibility to motion sickness respectively [63], [103]. Similarly, measuring the difficulty in using gamepad may also depend on an individual's practise of using a gamepad such as for playing videogames. Therefore, the pre-exposure questionnaire also contained items from MSSQ [103], (Items 1-3, Appendix 3.4), ITQ [63] (Items 4-30, Appendix 3.4) and on **how often they had used gamepads before** (Item 31, Appendix 3.4).

However, for this study items 11 and 12 from the original ITQ by Witmer and Singer (1998) [63] (see Appendix 3.3) asking participants about their casual reading habits, were deemed inappropriate and therefore excluded. This is because the participants constituted staff and students from the University who usually have little time to read materials other than textbooks. Kennedy et al. (1993) [98] insist on applying SSQ post exposure with a pre-exposure screening of unhealthy participants by asking them to self-report their state of fitness just before the evaluation. This was done using items 7 and 14 of the pre-exposure questionnaire.

4.4.5.2. Post-exposure questionnaire:

A post-exposure questionnaire (see Appendix 3.5) collected participants' experience after completion of their VE exposure and performing the tasks. Items 1-16 of the questionnaire were taken from SSQ, while items 17-45 were taken from PQ. The simulator used for this research does not allow participants to examine objects in VE from multiple viewpoints, or touch or manipulate them. Therefore, items 20, 17 and 21 of the original PQ (see Appendix 3.1) were excluded from post-exposure questionnaire. The questionnaire also had two open-ended questions, asking participants to feedback on the evaluation environment i.e. soundroom and method of data collection i.e. the questionnaires.

4.4.6. Experimental design

A repeated-measures design was selected for the study. A bias may result due to the sequence of presentation of each visual scenario. To eliminate the sequence effect, participants were exposed to pre-determined sequences using the 'balanced 6 X 6 Latin square' method [104]. Before presenting them with the 6 experimental conditions (1A, 1B, 2A, 2B, 3A, and 3B) every participant was exposed to the 3 locations one by one without using the target car in a sequence determined by 'complete counterbalancing' [104]. This was done to familiarise participants with using the gamepad. Appendix 4 shows the presentation sequence used for each participant. After exposure to each location, participants were asked if they required another practise trial of gamepad and if they answered yes, they were exposed to the same location once again.

4.4.7. Procedure

The experiment was conducted in the following manner:

I. A written informed consent was obtained from the participant

II. Participant was requested to complete pre-exposure questionnaire on paper.

III. Participant was briefed about the task and was exposed to the three scenarios (car-park, traffic lights, T-junction) as trials to get accustomed to the gamepad.

IV. After the trials, (s)he was exposed to the 6 experimental conditions in the pre-determined sequence. The participant's performance model files were recorded. There was minimum 10 seconds pause with no stimulus between the exposures.

V. After the experiment finished, participant was requested to answer post-exposure questionnaire on paper.

4.5. Study 1: Results

4.5.1. Simulator sickness experienced by participants

No participant left the experiment due to any form of sickness. Based on the original equations presented by the authors of SSQ the total simulator sickness scores, and the individual scores for nausea, oculomotor and disorientation were calculated (see [98] and appendix 3.2 for details). Based on the original equations the range of total simulator sickness, nausea, oculomotor and disorientation score are 0 – 235.62, 0 – 200.34, 0 – 159.18, 0 – 292.32 respectively. In literature the scores below 50 are considered low and scores about 60 – 100 are considered moderate [98].

The mean simulator sickness experienced by the participants after approximately 25 minutes of exposure to the VE was 39.74 (SD = 60.42). The mean Nausea, Oculomotor and Disorientation experienced by participants after 25 minutes of exposure to the VE were 28.62 (SD = 48.41), 24.64 (SD = 35.1), 60.9 (SD = 91.79) respectively. Figure 4.5 shows the nausea, oculomotor and discomfort experienced by the individual participants.

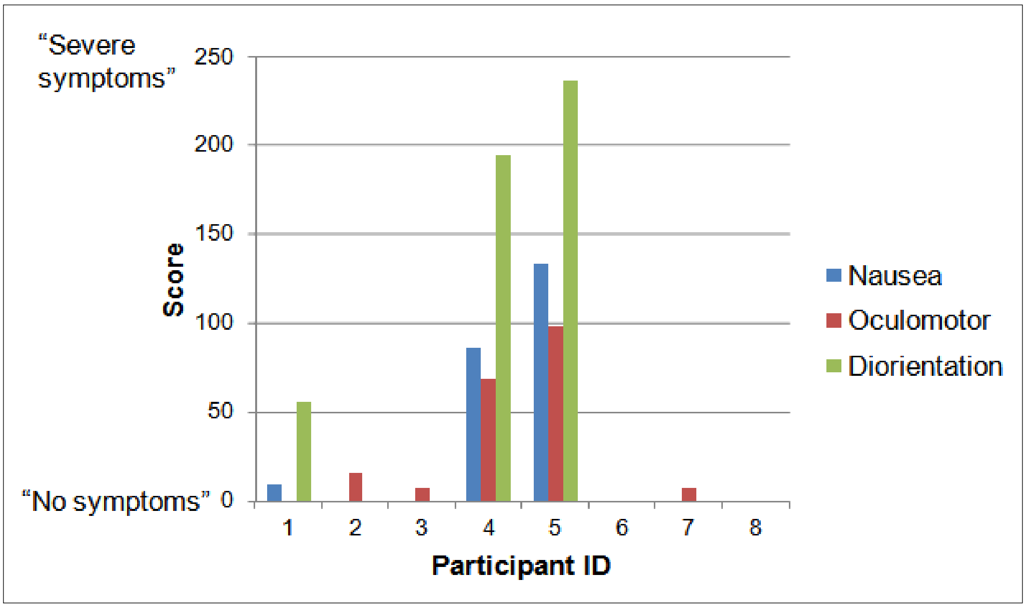


Figure 4.5 Nausea, Oculomotor and Disorientation experienced by participants upon approximately 25 minutes of exposure to the VE setup of this research.

Therefore, overall participants experienced low symptoms of nausea, oculomotor and overall simulator sickness upon 25 minutes of exposure to the VE presented using the soundroom-ESS set-up. However, they experienced moderate symptoms of disorientation when exposed to this VE for 25 minutes. From Figure 4.5 it could be seen that while all other participants experienced very low to no symptoms, participants 4 and 5 experienced moderate to high symptoms of sickness. These were the same participants who had initially reported having moderate to high susceptibility to motion sickness (Table 4.1).

4.5.2. Presence experienced by participants

Table 4.4 shows the means scores obtained from the post-exposure PQ. The scoring was done on a scale of 1 to 7. For comparison, the scores from 3.5 to 4.5 were considered moderate, scores > 4.5 considered high and scores < 3.5 considered low. Overall the participants experienced moderate level of presence, mean score = 4.1, when immersed in the VE.

Table 4.4 Participants' scores on the data collected from the presence questionnaire

Measure of the various aspects of feeling present within the VE	Mean	SD
Involved/Control	4.38	1.00
Natural	3.50	1.27
Auditory	4.42	1.34
Resolution	4.13	1.64
Interface Quality	3.71	0.55
Total Presence	4.10	0.79

Involvement/ Control in the VE (mean score = 4.4): The participants found the visual aspects of the VE and the overall VE experience involving. They perceived to have an effective control of the events in the VE and found the VE quite responsive to the participant-initiated inputs from the gamepad.

Naturalness of the VE (mean score = 3.5): Although participants found the VE consistent with reality, they found the navigation mechanism using the gamepad as unnatural.

Auditory aspects of VE (mean score = 4.4): Participants found the sound reproduction inside the soundroom impressive. They could effectively identify and localize sounds and found the overall auditory aspect of the VE involving.

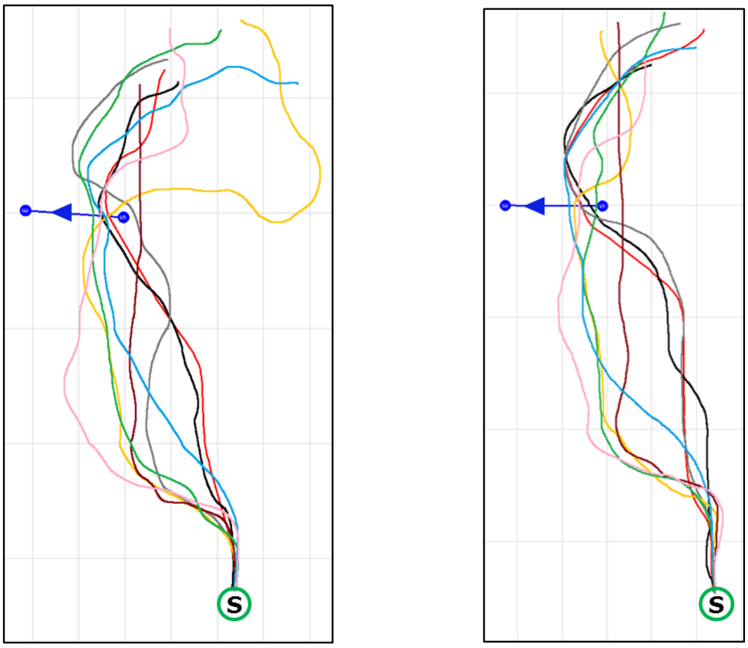
Screen Resolution (mean score = 4.1): Participants were moderately satisfied by the visual resolution of various objects in the VE.

Interface Quality (mean score = 3.7): Participants found the navigation device (gamepad) slightly distracting with their navigation task. However, participants scored moderately on the display and the sound devices being very little interfering with their navigation tasks.

4.5.3. Feasibility of the interactive mode of evaluating (H)EV sounds

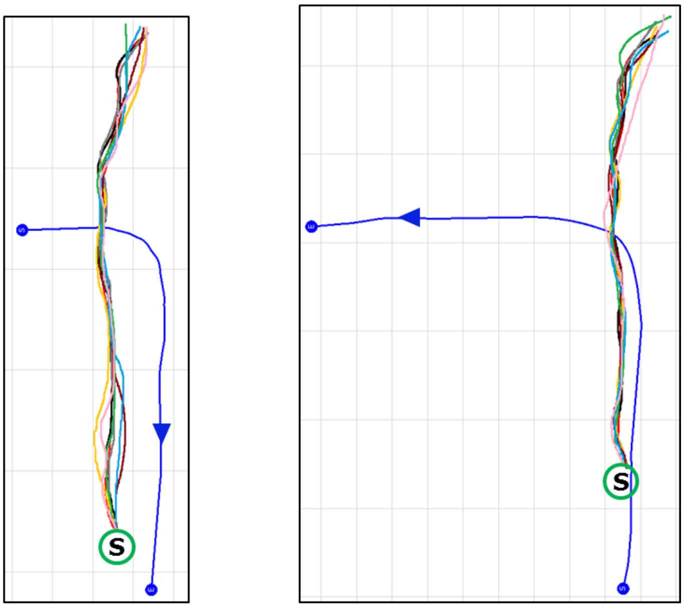
4.5.3.1. Participants' repeatability

Figure 4.6 to Figure 4.8 show the trajectories of the target car and the pedestrian as navigated by each participant. It is observed that the trajectories followed by the participants are very different from each other for experimental conditions 1A and 1B (Figure 4.6). However, the trajectories are very similar for experimental conditions 2A and 2B (Figure 4.7). For experimental conditions 3A and 3B, the trajectories differed when pedestrian arrived at the T-junction, where the researcher had planned for the pedestrian to interact with the target car (Figure 4.8). Since the participant's interaction with the target car differed in four out of six experimental conditions, overall the experimental conditions were not repeatable across participants. Furthermore, on two occasions participants were temporarily stuck as they mishandled the controls of the gamepad and could not reach the target car on time. Thus, they failed to interact with the target car. Thus, overall the repeatability across participants was poor.



Scenario 1A Scenario 1B

Figure 4.6 A comparison of trajectories navigated by participants in the visual scenario 1: car park. Here, S = pedestrian's starting position, and arrow indicates the direction of target EV's trajectory.



Scenario 2A Scenario 2B

Figure 4.7 A comparison of trajectories navigated by participants in the visual scenario 2: crossroad with traffic lights. Here, S = pedestrian's starting position, and arrow indicates the direction of target EV's trajectory.

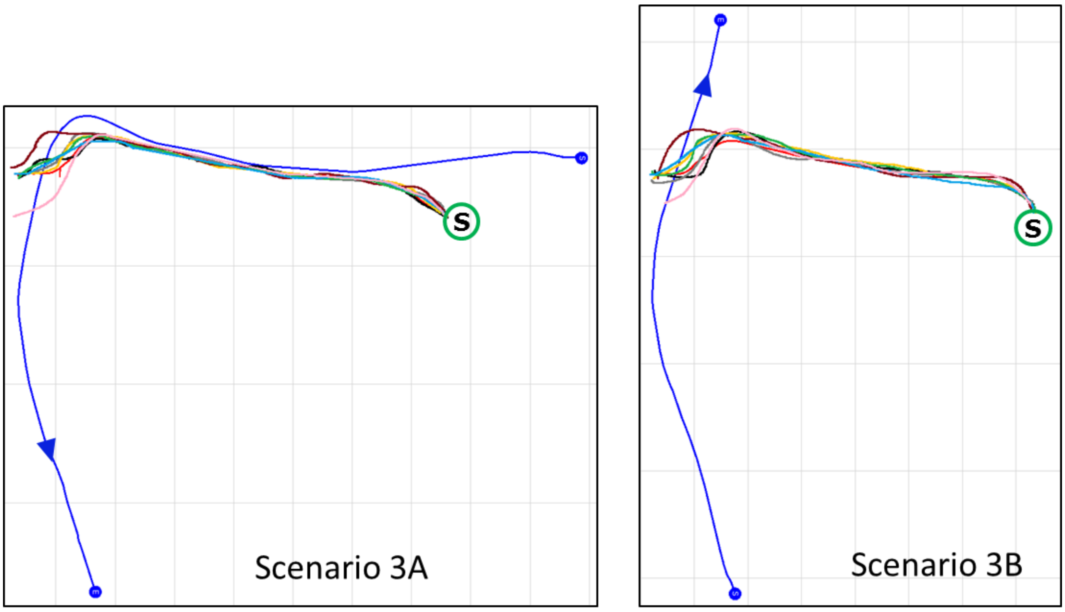


Figure 4.8 A comparison of trajectories navigated by participants in the visual scenario 3: T-junction with no traffic lights. Here, S = pedestrian's starting position, and arrow indicates the direction of target EV's trajectory.

4.5.3.2. Participants' feedback

Table 4.5 summarises the participants' feedback by categorising it on various aspects related to the overall experiment. Overall, participants found the current gamepad controls and settings very unnatural as a means to navigate a VE from the point of view of a pedestrian. This was primarily because the current gamepad controls do not have facility for participants to rotate the pedestrian's head while standing or stationary. The participants commented that when navigating the VE they would like to be able to rotate their heads when stationary specially to see vehicles on their sides before crossing any signal or road junction. Moreover, the current ESS facilities always start the interactive mode with a pedestrian standing in the middle of the road. Participants found this scary and would like to start directly on a pavement.

Table 4.5 Participants' feedback on study 1

Feedback category	Comments	Number of responses
Navigation and Navigation device – "Gamepad"	"I want to be able to rotate head when standing stationary"	3
	"More flexible head rotation, when walking or standing would enable to see vehicles coming from either side to help decide when to cross a signal, junction/ turning."	3
	"Gamepad settings seemed unnatural"	2
	"I disliked the controlling device"	1
	"Time delay in gamepad input and visual output"	2
	"Starting position on the road is scary. I would like to start on the pavement"	3
Audio	"The sound reproduction and surround sound was good!"	2
Soundroom	"No fresh air in the room. May get suffocating after some time"	2
	"It was too hot and I felt dizzy from the beginning of the experiment"	1
	"Like the screen shape and visual quality. It made VE more realistic!"	1
Questionnaire	"Some wordings were confusing"	4
	"Did not fully understand the what extreme ends of the scale represented"	1
	"Reduce the number of questions"	1

4.5.3.3. Level of difficulty/ease of performing evaluations

The total exposure lasted an average of 25 minutes varying from 20 – 28 minutes for individual participants. Every participant took 3 trials with the gamepad, 1 in each VE location, and none demanded any additional training. Participants in general found it difficult to perform the navigation task along with the evaluation of target car sounds. Therefore, on six occasions out of total 48 occasions (6 experimental condition for every 8 participant) participants (n=3) could not perform the evaluation task.

4.6. Study 1: Discussions

Although the interactive mode looks promising, it has some disadvantages with respect to the non-interactive mode of evaluation. Firstly, the experimental conditions are not repeatable across participants and every individual had different patterns of navigating the VE and interacting with the target car. This led to differences in the visual and auditory stimuli experienced between individuals for the same conditions (same target car sound and same target car's manoeuvre). Therefore, participants' results cannot be compared or combined across experimental conditions. As such, this interactive way of evaluating (H)EV sounds with the current ESS functionality is only suitable for descriptive or exploratory studies and not for cause-and-effect studies that involve inferential statistics. Moreover, poor repeatability of experimental conditions across participants also makes the experiments less reliable.

Secondly, the duration of the experiment including the navigation training is 25 minutes for six experimental conditions, which gives 4.17 minutes per condition. This implies that interactive way of evaluating (H)EV sounds could be very tiring and therefore unsuitable for experiments involving more than about 10 experimental conditions.

Improved participant training in navigating the VE, easier to learn and use navigation mechanisms and using larger number of participants may lead to common patterns in participant's manoeuvres. This may improve experiment's repeatability across participants.

The total simulator sickness and the nausea, oculomotor and disorientation experienced by the participants in the VE set-up of this research is comparable to most accepted modern VE systems [95], [96], [99]. According to Kennedy et al. (1993) the symptoms found in the present study are low compared to a large number of VE/VR systems studied by them [98]. The nausea, oculomotor, disorientation and overall simulator sickness can be further reduced by excluding people especially female who report having high susceptibility to motion sickness.

The participants experienced moderate level of presence and immersion in the VE set-up used in this research. The participants found the visual and auditory aspects of the VE and the overall VE experience very involving. They perceived to have an effective control of the events in the VE and found the VE fairly responsive to the participant-initiated inputs from the gamepad. At the same time, participants were impressed with the sound reproduction and localization inside the soundroom.

Participants found the navigation device (gamepad) slightly distracting with their task at hand. This was primarily due to the difficulty to learn and control navigation through the gamepad. Two participants could not reach the target car on time because they mishandled the controls on the gamepad. Although participants found the VE consistent with reality, they complained that the navigation mechanism using the gamepad was unnatural. Participants suggested that the navigation should have functionalities to rotate the pedestrians' head while stationary and starting the pedestrian directly on a road pavement than on the road. The inclusion of these functionalities would require a software enhancement of ESS but would help improve participant' experience and easier navigation in the VE.

4.7. Summary

This chapter describes study 1 that examined the fidelity of the experimental setup used for this research and the quality of the user experience. The soundroom-ESS setup was found immersive with sufficient degree of involvement/control, naturalness, resolution, and interface quality. Overall participants experienced moderate level of presence and very low symptoms of simulator sickness within the experimental setup. This was comparable to accepted and modern VE setups. It also explored the feasibility of the interactive mode of evaluating (H)EV sounds. The interactivity increased experiments' ecological validity as participants interacted with the vehicle more naturally by freely navigating just like a real world scenario. However, interactivity reduced the experiment's reliability and increased the experiment duration. Thus, using a predefined scenario (non-interactive mode) is preferred for studies 2 and 3.

Chapter 5: Application and Testing of Methodology-v1

5.1. Introduction

Chapter 2 presented a critical review of the state-of-the-art automotive sounds' evaluation methods in the context of experimental design and cognitive psychology. Based on the knowledge gained methodology-v1 was proposed in chapter 3 to holistically evaluate (H)EV exterior sounds on the criteria that they ensure pedestrians' safety and reinforce the vehicle brand. For this purpose, an experimental approach was suggested that assesses the detectability of these sounds and emotional evaluation of the vehicle based on listening to its sounds.

This chapter describes Study 2 [105], [106], which constitutes an evaluation experiment that was designed and conducted in accordance with the proposals made as part of methodology-v1. This study applied the methodology-v1 to an experiment that simulated a pedestrian interacting with a target EV in one of the traffic scenarios critical to pedestrians' safety. The chosen traffic scenario was a pedestrian waiting to cross the road in a T-junction and the target EV approached the junction travelling at constant speed of 10 mph (16.1 kph). The methodology-v1 is then reviewed in light of the results of the experiments.

5.2. Study 2: Objectives and Hypotheses

The study had the following objectives:

I. To assess reliability, control and ecological validity of methodology-v1 when it is applied to a pedestrian interacting with an (H)EV in a traffic scenario critical to pedestrians' safety.

The study also tested the following hypotheses:

I. **Hypothesis 1:** Pedestrians' evaluation of vehicle exterior sounds is affected by the change in the vehicle's arrival time.

   a. **Hypothesis 1a:** Pedestrians' rate of detecting a vehicle based on its exterior sounds is affected by the change in the vehicle's arrival time.

   b. **Hypothesis 1b:** Pedestrians' perceptual evaluation of subjective attributes of a vehicle exterior sound quality is affected by the change in the vehicle's arrival time.

II. **Hypothesis 2:** Pedestrians make detection errors in the presence of a real world ambient soundscape.

5.3. Study 2: Experiments

5.3.1. Participants

The participants were recruited from the study population set for this research (see 3.4.1). The study was designed for 2X15 repeated measures ANOVA. Twenty-four was the minimum number of participants required for this analysis, to achieve a minimum statistical power of 0.8 [82] at α-error probability of 0.05 with a medium effect size, f= 0.25 [82], as calculated by Software G*Power 3.1.7 [81]. However, the study used 31 experimental conditions (see 5.3.5) the presentation orders of which were randomized using a 31X31 balanced Latin square [79]. Therefore, having participants as a multiple of 31 would ensure a complete counterbalancing of the presentation order of the experimental conditions [79].

Therefore, final data was obtained from 31 participants. Figure 5.1 summarises the general characteristics of the participants used in this study.

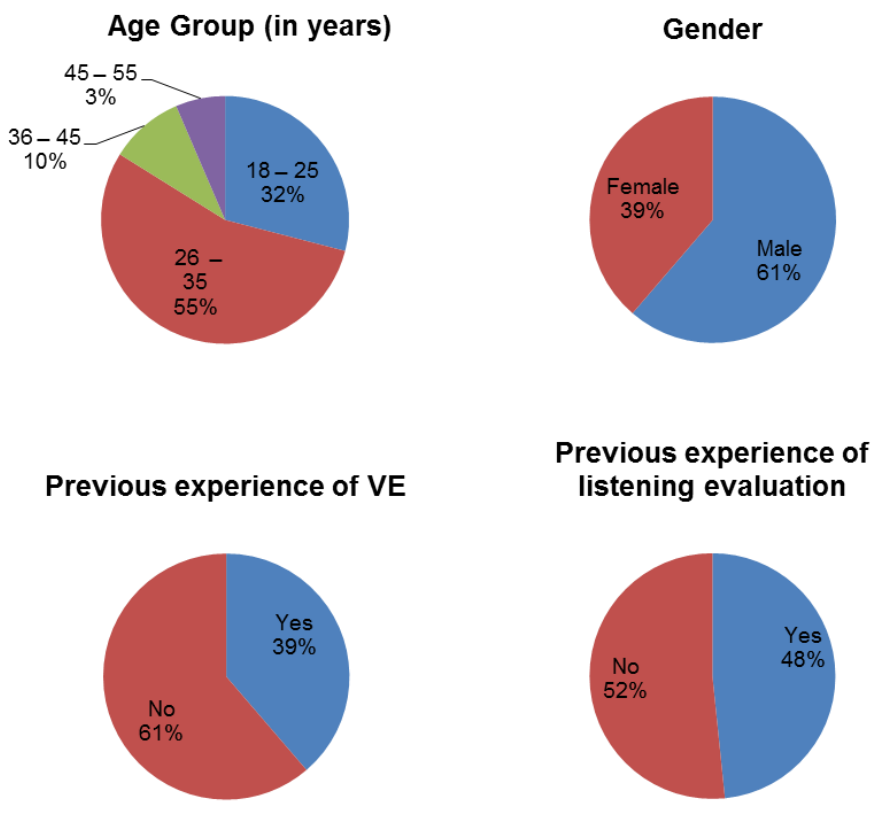


Figure 5.1 A summary of the general characteristics of the participants recruited for study 2

Participants were 19 males and 12 females with the modal age group of 26-35 years, comprising the staff and students from the University of Warwick. A majority of them (n=19) did not have any previous experience of VE exposure whereas half of them (n=16) had participated in a listening evaluation before.

5.3.2. Evaluation environment

All evaluations were conducted in the Soundroom-ESS set-up (see 3.5.3). Figure 5.2 shows the evaluation environment the participant was exposed to.

Figure 5.2 Evaluation environment in study 2.

5.3.3. Stimuli

The literature review has identified critical scenarios of pedestrian-vehicle interactions (see 2.2.3). Therefore, in line with previous research studies as well as study 1 of this research project, the visual and auditory stimuli for this study were chosen to include these critical scenarios. This is because these scenarios being critical to pedestrians' safety require the use of additional sounds from (H)EVs and also provide more relevant context.

5.3.3.1. Visual stimuli:

The visual stimuli is described below as a combination of the virtual town ('Hitchin') location, the pedestrian's manoeuvre, and the target vehicle's manoeuvre.

Virtual town location: The participant was exposed to a straight road ending in a T-junction with no traffic lights and no visible traffic (Figure 5.3). This junction mimicked a real world junction and it had houses and buildings lining along each side of the road.

Pedestrian's manoeuvre: The participant experienced himself/herself as a pedestrian walking along the pavement of the road at a constant speed of 3 mph (4.83 kph) (Figure 5.3). After walking 10 seconds, the pedestrian arrived at the junction and waited there until the target vehicle passed by. Everything that a participant saw corresponded to the things that the pedestrian in the VE would see when carrying out this manoeuvre. For example, the participant saw the objects of the virtual town move opposite to his/her direction of motion when the pedestrian walked along the pavement. Similarly, when the pedestrian paused at the junction, the participant saw the visuals pause at the junction (see Figure 5.2). Just like in a real world junction, the participants' view was restricted by buildings on either side of the road (Figure 5.3).

Target vehicle's manoeuvre: An electric car started from one of three distant off-screen positions on the road perpendicular to the pavement that the pedestrian was currently walking up. It travelled at a constant speed of 10 mph (16.1 kph), emitting a sound from its speakers, and passed by the junction. The vehicle appeared on-screen at 21.4 s, 29.7 s or 36.6 s from the start of the visuals.

The virtual town's traffic system was modelled on the UK based left-side traffic system. In visual stimulus 1, the car travelled in the direction from pedestrian's left hand side to the right hand side while travelling along the road furthest away from the pedestrian's standing position. In the virtual town, this road was modelled to be situated at a perpendicular distance of 10.5 meters from the pedestrian's standing position. In visual stimulus 2, the car travelled in the direction opposite to that of visual stimulus 1 from pedestrian's right hand side to the left hand side while travelling along the nearest road situated at a distance of 5.5 meters from the pedestrian. Figure 5.3 shows the layout for both visual stimuli together.

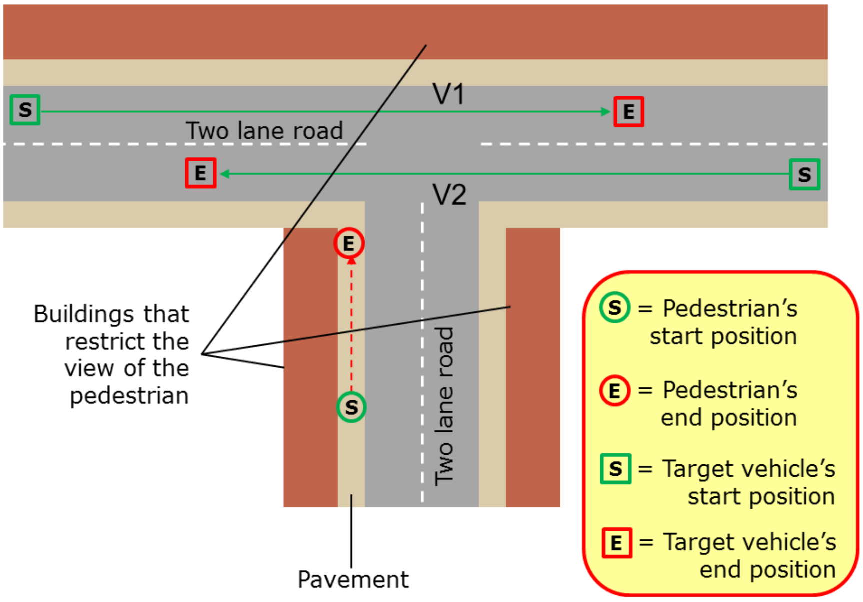


Figure 5.3 Schematic of the visual scenario for study 2. Red dotted lines indicate a pedestrian's path as experienced by a participant. Green solid lines indicate target vehicle's path for visual stimulus 1 ("V1") and visual stimulus 2 ("V2").

5.3.3.2. Auditory stimuli:

Fifteen sounds synthesized from engine recordings, pure tones signals, and tire sounds were used as sample target car's exterior sounds. Their equivalent SPL was in the range of 48 to 61 dB(A), all sounds were broadband with at least 1 signal in the range 160 – 5000 Hz, and none of these sounds resembled siren, horn, chime, bell, alarm, animal and insect sounds. However, two sounds (Sound 5 and 6) were melodious sounds. Therefore, the sounds comply with the latest (H)EV sounds legislation namely Federal Motor Vehicle Safety Standard (FMVSS) [24], Japan's AVAS (Approaching Vehicle Audible System) guidelines [21] and the UNECE's

Global Technical Regulation (GTR) [23], [25]. An 18 s, 42 dB(A) binaural recording made in a parking space was played in a loop as an ambience soundscape for every stimulus. To match the visual scenario, this ambience soundscape included sounds of regular bird chirping and light winds, and some occasional distant traffic. No moving vehicle was visible during the actual sound recording thus; there were no noticeable sounds of nearby vehicles. Table 5.1 and Table 5.2 describe the subjective content and the key metrics respectively of the sounds used in this study.

Table 5.1 Subjective description of the target car sounds i.e. sound 1 to sound 15, and the ambient soundscape used in study 2.

Sound ID	Description
Sound 1	A twin peak signal composed of sinusoidal and irregular waves with peaks frequency at 650 Hz and 2500 Hz and a dip at 1000kHz [37]
Sound 2	Tire rolling sounds mixed with low human vocals
Sound 3	A choral sound
Sound 4	A clear tone
Sound 5	A melody
Sound 6	A melody
Sound 7	Sound like a hovering of a helicopter
Sound 8	Simulated jet engine sounds
Sound 9	A low friction sound
Sound 10	Sound of an engine idling continuously
Sound 11	A humming sound mixed with tire rolling sound
Sound 12	Pure tones signals looped to sound like a spaceship
Sound 13	A sports engine sound
Sound 14	Sound simulated from human vocals
Sound 15	Exterior sound of a luxury car (less engine more tire sound)
Ambience	An 18s binaural recording made in a quiet car park

Table 5.2 Key psychoacoustic metrics of the target car sounds i.e. sound 1 to sound 15, and the ambient soundscape used in study 2.

Sound	SPL (dB(A))	Loudness (sones)	Sharpness (acum)	Roughness (asper)
Sound 1	55	5.8	1.46	0.46
Sound 2	54	4.8	0.41	0.09
Sound 3	55	5.8	0.36	0.04
Sound 4	48	7.7	0.75	0.31
Sound 5	61	9.9	0.52	0.01
Sound 6	52	5.5	0.52	0.06
Sound 7	55	7.2	1.08	1.72
Sound 8	53	6.2	0.43	0.00
Sound 9	51	6.1	0.59	0.41
Sound 10	51	6.2	0.81	0.50
Sound 11	52	6	0.52	0.38
Sound 12	60	8.8	1.19	0.50
Sound 13	57	9.8	0.98	1.84
Sound 14	58	9.3	0.52	0.22
Sound 15	52	7.9	0.79	0.14
Ambience	42	4.4	0.99	0.15

5.3.4. Measures

Participants were given an electronic touch screen tablet with the ESS-linked evaluation interface. Figure 5.4 shows the evaluation interface. The current ESS facility supports interfaces with scales but not touch buttons. Additionally, the current ESS facility does not support interfaces with scales that have words to anchor every number on the scales. Therefore, numbered semantic differential scales with semantic words at the extreme ends have been used to collect measures (Figure

5.4). Such scales have had successful applications in the field of automotive sound quality [71], [72], [107]. Hence, these scales were deemed appropriate for this research within the current ESS-linked software limitations. In accordance with methodology-v1 (see 3.3.2), the following measures were collected.

5.3.4.1. Detection rate

In line with most research involving quiet vehicles, detection rate (how fast or early is the vehicle approach detected) was evaluated using **"time-to-vehicle arrival**". Time-to-vehicle arrival is defined here as: "*the time in seconds taken by the target car to appear on screen from the instant it was detected by the participant*". A detection scale was used to record the time of vehicle detection. Participants were instructed to slide the detection scale on the ESS interface (first scale in Figure 5.4) to any value by moving the centre button of the slider as soon as they heard or saw a vehicle approaching. If they later thought they had incorrectly perceived hearing the car or moved the scale mistakenly, they were instructed to slide the detection scale again when they thought they started hearing the car.[1] The interface recorded the time of every instance a participant pressed or moved the scale with a least count of 0.01 seconds. The time-to-vehicle arrival was calculated by subtracting the time when the participant last moved the detection scale from the time the car appeared on the screen. In order to eliminate negative values, the time-to-vehicle arrival was given a value of zero whenever a participant did not press the detection scale or pressed the scale after the car appeared on screen.

[1] This was done because during pilot testing using two participants (1 male, 1 female), both of them commented that they thought they had heard the car, pressed the scale, and later realized that the sound was another sound in the ambient soundscape rather than the target car's sound.

5.3.4.2. Impression of the vehicle brand

Participants were asked to evaluate the impressions of the target EV, which is how powerful or pleasant the EV is perceived from listening to its sounds, on 7-point semantic differential scales of "**weak – powerful**" and "**unpleasant – pleasant**" [28]. Participants registered their evaluation scores by sliding the corresponding bi-polar semantic scales in the ESS interface to a value from 1 to 7 (Figure 5.4).

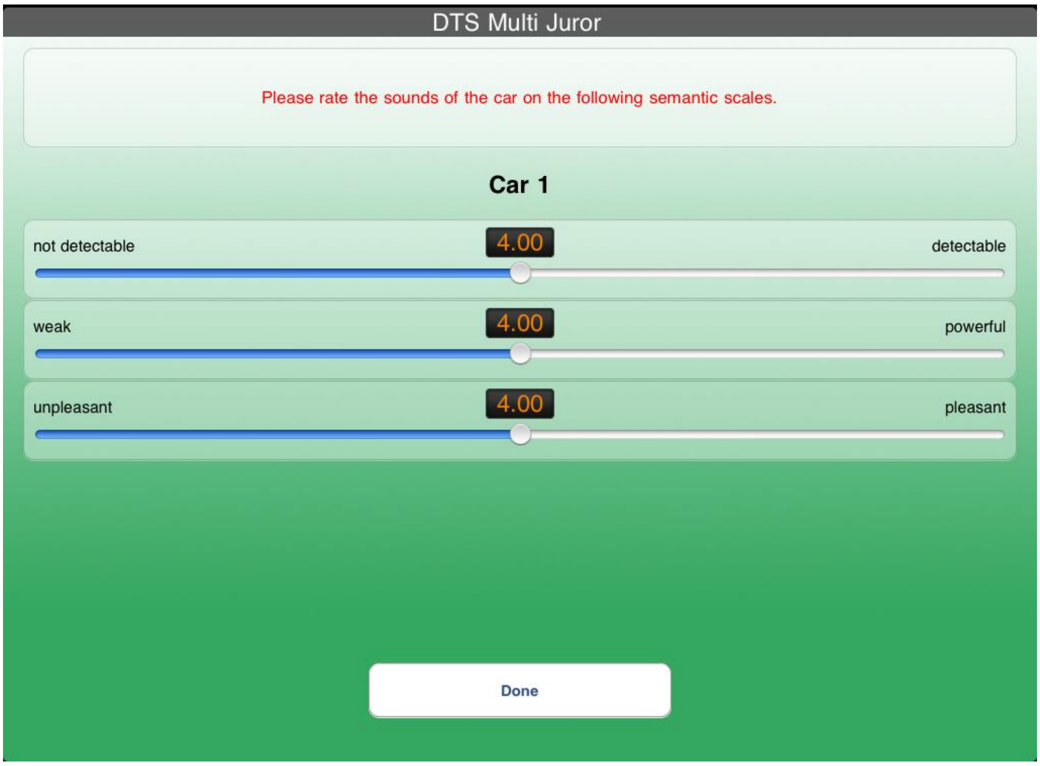


Figure 5.4 ESS-linked evaluation interface for study 2.

5.3.4.3. Participants' feedback:

After the experiment, participants were asked to provide feedback on their experience of the experiment and suggestions, if any, to improve the experiment.

5.3.5. Experimental design

A 2X15 repeated measures design was used with the following independent variables and their corresponding levels:

I. Target car's approach direction and travel distance :
   a. Level 1: target car arriving from pedestrian's left hand side travelling along the lane 10.5 m away from the pedestrian's standing position
   b. Level 2: target car arriving from pedestrian's right hand side travelling along the lane 5.5 m away from the pedestrian's standing position

II. Target car's sound: It had 15 levels, sound 1 to sound 15.

Thus, a 2X15 repeated measures design gave 30 different experimental conditions using every combination of the 15 target car sounds and the two approach directions with travel distance. The first experimental condition, the target car emitting sound 1 and approaching from pedestrian's left hand side, was repeated for every participant to check if participants' responses were repeatable. Therefore, each participant was exposed to 31 experimental conditions.

For this experiment, target car's arrival time was not taken as a repeated measures independent variable because this would have increased the experimental conditions to 90 (2X3X15) thereby heavily increasing the experimental duration. However, to test the hypothesis 1 (see 5.2) the arrival times of the target car was used as a covariate and varied for each target car sound using complete counterbalancing across the participants, but only using partial counterbalancing within the participants Appendix 5 shows the details of how arrival time was varied for each sound for every participant.

Exposure to a fixed sequence of experimental conditions may bias the results due to practice effects (participants become more experienced and better at the task as the experiment proceeds) [79], and fatigue effects (participants get tired as the experiment proceeds) [79]. The presentation order of the experimental conditions was therefore randomized using the 31X31 ‘balanced Latin square’ method to control such effects [79]. Appendix 5 contains the 31X31 balanced Latin square matrix made of 31 unique presentation sequences.

The presentation order of scale items was fixed by keeping positive adjectives - powerful and pleasant on the right and negative adjectives - weak and unpleasant on the left for the first 16 participants. The scales were reversed for the rest. This was done to check for any acquiescence bias or pseudo neglect bias [75].

5.3.6. Procedure

The experiment was performed on each participant one at a time in the following manner and lasted for about 40 minutes.

I. Written informed consent was obtained from the participant.

II. Participant reported his/her age, gender and if they had previous experiences with any VE or listening evaluation. If and only if the participant self-reported as feeling “well” (s)he was allowed to proceed.

III. Participant was briefed about the experiment.

IV. Seven second clips of the 15 target car sounds were played in the absence of the ambient soundscape followed by the ambient soundscape clip played separately to familiarise the participant of the variety of sounds used in this experiment.

V. Since the participant had heard the type of sounds used for the target car, (s)he was instructed to detect these sounds without considering if these sounds could be recognized as emanating from a car.

VI. Participant was instructed to first detect the car aurally or visually and then make a relative rating about the powerfulness and pleasantness of the target car based on its sound.

VII. Participant was exposed to a trial car for practice followed by the exposure to the experimental conditions and (s)he completed the task.

VIII. Participant was thanked, debriefed and feedback was collected.

5.4. Study 2: Results

5.4.1. Error in detection

Data recorded by interface showed that 68 % of participants (21 out of 31) pressed the detection scale more than once. This supports the hypothesis 2 of this study, implying that there is a high probability that participants may detect a target vehicle sound incorrectly in presence of a real world ambient soundscape.

5.4.2. External reliability

Paired t-tests found no significant difference between the participants' rating of the target car's powerfulness, $t(30) = -.97$, $p>.05$; pleasantness, $t(30) = .53$, $p>.05$, and detection rate, $t(30) = -.77$, $p>.05$, upon repeating the first experimental condition. This implies that the research method, which here is methodology-v1 applied in the soundroom-ESS set-up, accurately reproduces the results upon repeating an experimental condition. Thus, this experimental study was considered reliable. Since there was no significant difference, the mean data of the repeated experimental conditions were used for further analysis. This new data set satisfied all assumptions of ANOVA and ANCOVA (Appendix 6).

5.4.3. Effect of target vehicle's arrival time

A repeated measures ANOVA could not be performed using arrival time as an independent variable, as each car sound was not presented at every arrival time for every participant. Therefore, to check the effect of arrival time the repeated measures data was entered into SPSS in the form an equivalent independent group design thus getting 930 (31X30) independent data. ANCOVA was used for analysis to eliminate the effect of individual differences by using the participant ID as a covariate. The data satisfied all assumptions of ANCOVA (Appendix 6). Independent group ANCOVAs was performed using arrival time as the independent variable, participant ID as the covariate, and powerfulness, pleasantness and detection rate as dependent variables. Table 5.3 shows the results of this analysis.

The covariate participant ID was not significantly related to the target car's detection rate ($F(1, 926) = 1.52$, $p>.05$, $r=.04$) or to the car's powerfulness ($F(1, 926) = 3.31$, $p>.05$, $r = .06$); but had significant relation with the car's pleasantness ($F(1, 926) = 4.77$, $p<.05$, $r=.07$).

Arrival time significantly affected target car's detection rate after eliminating the effect of individual differences (see Table 5.3). Planned contrasts revealed that arrival time of 36.6 s significantly decreased the target car's detection rate compared to arrival time of 21.4 s, $t(926)= 7.51$, $p<.05$, $r= .24$, and also compared to arrival time of 29.7 s, $t(926)= 3.42$, $p<.05$, $r= .11$. Thus, the later the car arrived, the slower the participants detected it. This supports the hypothesis 1a of this study.

Table 5.3 Effect of manipulating target vehicle's manoeuvre on pedestrians' evaluation of EV sounds in study 2.

Factor	Level	Statistics	Detection rate (s)	Powerfulness	Pleasantness
Arrival time	**21.4 s**	**Mean**	14.00	4.20	3.76
		SD	8.82	1.59	1.57
	29.7 s	**Mean**	10.89	3.98	3.80
		SD	9.87	1.64	1.49
	36.6 s	**Mean**	8.28	3.85	3.53
		SD	9.73	1.64	1.53
	—	**Effect on measures**	$F=28.245$, $p=.00^{**}$, Partial $\eta^2=.057$	$F=3.735$, $p=.024^{*}$, Partial $\eta^2=.008$	$F=2.849$, $p=.058$, Partial $\eta^2=.006$
Direction + travel distance for arrival time 1	**Left**	**Mean**	13.492	4.000	
		SE	.394	.116	
	Right	**Mean**	14.978	4.402	
		SE	.394	.116	
	—	**Effect on measures**	$F=7.124$, $p=.008$, Partial $\eta^2=.025$	$F=5.981$, $p=.015$, Partial $\eta^2=.021$	
Direction and travel distance for arrival time 2	**Left**	**Mean**	11.174	3.772	
		SE	.525	.116	
	Right	**Mean**	10.732	4.196	$F(1,30) = 1.87$, $p>.05$
		SE	.525	.116	
	—	**Effect on measures**	$F=.353$, $p=.553$, Partial $\eta^2=.001$	$F=6.664$, $p=.010$, Partial $\eta^2=.023$	
Direction and travel distance for arrival time 3	**Left**	**Mean**	7.774	3.650	
		SE	.545	.118	
	Right	**Mean**	8.512	4.053	
		SE	.545	.118	
	—	**Effect on measures**	$F=.916$, $p=.339$, Partial $\eta^2=.003$	$F=5.847$, $p=.016$, Partial $\eta^2=.021$	

For arrival time: $df = 2$, $df_{error} = 926$; for direction + travel distance: $df = 1$, $df_{error} = 279$; and $^{*}p<.05$, $^{**}p<.01$

There was a significant effect of arrival time on target car's powerfulness after eliminating the effect of individual differences. Planned contrasts revealed that arrival time of 36.6 s significantly decreased car's powerfulness compared to arrival time of 21.4 s, $t(926)=2.7$, $p<.05$, $r=.09$, but not compared to arrival time of 29.7 s, $t(926)=.99$, $p>.05$, $r=.03$. Thus, the later the car arrived, the less powerful it was perceived by the participants. However, there was no significant effect of arrival time on pleasantness score after eliminating the effect of individual differences. Thus, the hypothesis 1b of this study was rejected.

5.4.4. Effect of car's direction of approach together with travel distance

Arrival time had no significant effect on the target car's pleasantness. Therefore, the original repeated measures data was used to examine the effects of the target car's approach direction with travel distance and target car's sound on pleasantness using repeated measures ANOVA with car's sound and car's approach direction with distance as independent variables and the target car's pleasantness as dependent variable. There was no significant effect of the car's approach direction on the pleasantness score (Table 5.3) ($F(1, 30) = 1.87$, $p>.05$).

Considering arrival time's significant effect on the target car's detection rate and powerfulness, the data was grouped into three sets relating to each arrival time. Separate independent group ANCOVAs were performed for each group using car's sound and car's approach direction with distance as independent variables; detection rate and powerfulness as dependent variables; and participant ID as covariate.

The covariate participant ID was not significantly related to the target car's powerfulness for arrival time of 21.4 s ($F(1, 279) = 1.95$, $p>.05$), 29.7 s ($F(1, 279) = .37$, $p>.05$), and 36.6 s ($F(1, 279) = 1.81$, $p>.05$); and also not significantly related to the target car's detection rate for arrival time of 21.4 s ($F(1, 279) = 1.11$, $p>.05$), 29.7 s ($F(1, 279) = .80$, $p>.05$), and 36.6 s ($F(1, 279) = 1.85$, $p>.05$).

After eliminating the effect of individual differences, the target car's approach direction together with the travel distance significantly affected the target car's powerfulness for every arrival time (see Table 5.3). In all three arrival time cases, paired comparisons revealed that the target car was perceived as more powerful when approaching from the right when it passed by along the lane nearer to the pedestrian's position.

After eliminating the effect of individual differences, the target car's approach direction together with the travel distance significantly affected the car's detection rate only for arrival time of 21.4 s. but not for arrival time 29.7 or 36.6 s. Therefore, the result of arrival time 21.4 s was considered as experiment error.

5.4.5. Effect of target car's sound

Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of target car's sound on pleasantness, $p<.001$. Thus, after applying Greenhouse-Geisser correction ($\varepsilon = .53$) the target car's sound significantly affected the target car's pleasantness, $F(7.43, 222.78) = 21.69$, $p<.001$.

After eliminating the effect of individual differences, the target car's sound significantly affected the target car's powerfulness for:

I. arrival time of 21.4 s ($F(14, 279) = 5.24$, $p<.05$)
II. arrival time of 29.7 s ($F(14, 279) = 7.35$, $p<.05$)
III. arrival time of 36.6. s ($F(14, 279) = 6.59$, $p<.05$)

Similarly, the target car's sound significantly affected the target car's detection rate for:

I. arrival time of 21.4 s ($F(14, 279) = 50.43$, $p<.05$)

II. arrival time of 29.7 s ($F(14, 279) = 29.93$, $p<.05$)

III. arrival time of 36.6. s ($F(14, 279) = 24.87$, $p<.05$)

5.4.6. Comparing sounds and psychoacoustic analysis

Table 5.4 compares the target car sounds based on the measures used. For comparison, the combined means were obtained by calculating the mean scores of all participants for the 30 experimental conditions and then taking the mean score of left and right direction of the car's approach for the 15 target sounds.

Table 5.4 Combines means for the 15 target car sounds for study 2

Sound ID	Powerfulness	Pleasantness	Detection rate (s)	SPL ($dB(A)_{eq}$)
1	3.92	2.98	7.61	55
2	3.38	4.52	6.91	54
3	4.58	4.23	15.09	55
4	3.4	3.65	1.6	48
5	4.58	3.38	17.6	61
6	3.33	4.93	14.99	52
7	3.8	2.55	10.01	55
8	3.6	3.95	8.33	53
9	2.83	4.73	11.44	51
10	4.17	3.85	3.04	51
11	3.42	4.35	6.08	52
12	5.28	1.97	32.08	60
13	5.3	2.88	5.52	57
14	5.1	3.97	12.43	58
15	3.97	3.5	12.51	52

A bivariate (Pearson) correlation analysis was performed among the measures and the key acoustic and psychoacoustic metrics for the 15 target car sounds (see Table 5.5). Powerfulness had a significant high correlation with the pleasantness score, r= -.613, p<.05. However, detection time was not significantly correlated to either powerfulness, r= .447, p>.05 or to pleasantness, r= -.356, p>.05.

Table 5.5 Pearson's correlation coefficients (r) between pedestrians' evaluation of EV sounds and the sounds' key acoustic and psychoacoustic metrics in study 2.

		Mean detection rate	Mean powerfulness	Mean pleasantness
Mean powerfulness	r	.447		
	p	.094		
Mean pleasantness	r	-.356	$-.613^{*}$	
	p	.192	.015	
Mean SPL (dB(A))	r	$.653^{**}$	$.772^{**}$	$-.531^{*}$
	p	.008	.001	.042
Mean Loudness (sones)	r	.317	$.732^{**}$	$-.589^{*}$
	p	.250	.002	.021
Mean Sharpness (acums)	r	.114	.275	$-.791^{**}$
	p	.687	.322	.000
Mean Roughness (asper)	r	-.184	.279	$-.558^{*}$
	p	.512	.313	.031
$^{*}p<.05$, $^{**}p<.01$				

From Table 5.5 it was observed that only mean A-weighted SPL had a significant correlation with the detection rate. Hence, a linear regression was performed to predict detection rate (in s) from the mean dB(A) values. The mean dB(A) significantly predicted the combined mean of the detection time, $F(1, 13) = 9.68$, $p < .05$, $R^2 = .43$. However, sound 12 did not fit the regression model, Cook's

Distance > 1.0. Additionally, from Table 5.4 a few anomalies were observed with respect to the SPL and detection rate relationship. For example, sound 13 was detected much slower than sounds 1 to 3, 6 to 9, 11, and 15, even though it had higher $dB(A)_{eq}$ than these sounds. Sound 6 had among the lowest $dB(A)_{eq}$ of the other sounds, but it was one of the fastest detected sounds.

5.4.7. Participants' feedback

Feedback from participants is arranged thematically in Table 5.6. All participants found the experiment enjoyable and did not suggest any improvement in experimental design. Pleasantness was not considered an appropriate semantic term for evaluating EVs (n=10). Some participants found detecting the vehicle difficult as they confused it with fluctuations in the ambient soundscape (n=7). As such having a 7-point scale for evaluating "detectability" would give them more confidence in their detection results (n=3). Participants found certain sounds unrecognizable or too "artificial" for a vehicle and suggested that the sounds should be tested for being recognisable as a vehicle (n=6).

Table 5.6 Participants' feedback of study 2

Feedback category	Comments	Number of responses
Overall experiment	"Experiment was enjoyable."	31
	No improvement suggested in the experimental design.	31
Choice of Semantics for emotional evaluation	"Pleasant seems an unusual choice of attribute for an electric car warning sounds"	7
	"How 'pleasant' relates to an electric car that emits a sound that is supposed to warn pedestrians of the vehicle approach"	7
Vehicle detection	"Reporting exact detection time was difficult due to confusion with background sounds"	7
	"I would feel more confident about my results if I could evaluate the detectability of sounds subjectively on a 7-point scale in addition to reporting the 'exact' detection time"	3
Vehicle recognition	"Some car sounds seemed artificial, simulated, and unlikely to be emanating from a vehicle."	2
	"Even though I detected these sounds during the experiment, I may not recognize them as vehicle sounds in real life."	4
	"You should also test if these sounds could be intuitively recognized as a vehicle sound."	6

5.5. Study 2: Discussions

The methodology-v1 was successfully applied to a pedestrian interacting with an EV in a critical traffic scenario of a town's T-junction. The methodology brought together the benefits of laboratory and on-road environments by achieving reliability and control while also providing the appropriate context. Additionally, the methodology had greater ecological validity compared to the existing automotive sound quality evaluation methods. Factors associated with the target vehicle's manoeuvre namely the vehicle's "arrival time", "approach direction" and "distance of travel" are influential in pedestrians' evaluation of (H)EV sounds. Therefore, care is needed in the design of these studies, by including these factors as part of the experimental design. Vehicle detection, in particular, is a more complex task and may involve detection errors.

5.5.1. Review of Methodology-v1

5.5.1.1. Reliability and control:

The methodology produces same results upon repeating an experimental condition, thus it is reliable. The experiment demonstrated the convenience and accuracy with which various experimental factors associated with the target EV namely; operating conditions (here 16.1 kph pass-by), arrival time, direction and distance of approach were controlled and altered as desired by the researcher. Varying these factors makes the methodology free from any expectancy biases that are present in conventional evaluations methods that use fixed arrival time, distance and direction of the target vehicle. The researcher was also able to maintain a desired ambient soundscape and the exact same visuals of a T-junction for all experimental conditions for every participant. Moreover, the experiments were conducted within a controlled environment of a closed semi-anechoic listening room (soundroom), therefore the researcher could maintain similar weather conditions namely, temperature, wind and lighting, for all experimental conditions for every participant. Overall, the experimental methodology is argued to achieve reliability and control.

5.5.1.2. Ecological validity:

Any laboratory or experimental study is usually criticized for not being generalizable to a real-world setting. The generalizability is in the form of (a) the methods, i.e. “if the experiment method and protocol represent the real world situation”; or (b) results, i.e. “if the results and conclusions drawn can be generalized to the real world” [76]. The former is estimated as ecological validity of a study whereas the latter as the external validity [76]. The presented study would be called ecologically valid if the methodology replicates the way pedestrians interact and evaluate a vehicle in a real world traffic environment. The following things ensured the ecological validity of the methodology-v1:

I. The participants experienced the target EV in the context of a real world traffic scenario. This was achieved using an appropriate visual scenario, real world ambient soundscape and audio stimuli corresponding to the EV’s manoeuvre.

II. Varying the target EV’s manoeuvre such as altering the EV’s arrival time, direction of approach and distance of travel path across the experimental conditions, much like in a real world scenario. This helped the people to think and pay a similar level of attention and process information obtained from various senses (visual and auditory) as in the real world. Thus, they were able to react and respond to the vehicle’s sound like a real world pedestrian.

III. Options to detect the vehicle as many times as the participant wanted.

5.5.2. Improving methodology-v1

5.5.2.1. Understanding and improving the method for vehicle detection:

The majority of participants (68 %) used the detection scale more than once. This indicates that there is a high probability (68 %) that a participant may detect a target vehicle sound incorrectly when indicating the first detection and therefore would want to detect the target vehicle sound again upon realising a mistake in previous detection.

The reason they provided for this was that they confused spikes in ambient soundscape with the target vehicle sound thus making an incorrect detection. This confusion could be because of the ‘unrecognisability’ of these sounds as car sounds. Therefore, whenever there were spikes in the ambient soundscape, due to sudden occurrences of transient ambient sounds such as wind, leaves and distant traffic, participants assumed it was the start of the electric car sound. Moreover, people expect cars to sound in a certain way that these sounds may not have, thus adding to difficulties in detection. In real-life scenarios, the total ambient soundscape comprises of variety of individual sounds including both vehicular and non-vehicular sounds. A pedestrian has to identify and detect a vehicle that may be approaching his/her path in the presence of many such ambient sounds. In these scenarios, as suggested by multiple instances of detection in this study, a pedestrian detects the vehicle continuously (at least until the instant (s)he is fully sure of the vehicle’s approach). Some participants preferred a semantic scale evaluating the car’s detectability in addition to recording the time they detected the car. This was because they felt more confident about the results they provided on a subjective scale than the detection time.

The above discussions indicate that real life vehicle detection is a more continuous and subjective process. Thus, vehicle exterior sound quality evaluation methods could be improved by making the vehicle detection tasks more representative of the real world process. To achieve this, the evaluation method should include a facility for participants to continuously evaluate the vehicle's detectability through options of re-recording the car's detection time as well as subjective evaluation of the vehicle's detectability. ESS helps in achieving this as participants can interact with the scales and record times of detection as well as the semantic scores continuously until they are satisfied with their evaluations.

The study also found that the participants' rate of detecting a car reduced with increase in the car's arrival time; the later the car arrived, the slower it was detected. This could be because in the existing vehicle exterior sound detection tests [9], [10], [33], [37], [38], or generally in any existing auditory detection tests [108] the target car sound to be detected is present from the very beginning of the stimulus. Therefore, participants when part of any auditory detection test expect to hear the target stimulus (here, the target EV sound) from the very beginning. This expectancy bias is also indicated by the participants' false detections made towards the beginning of the presentation of each experimental condition. Some authors also argue that a reason for slower detection could be due to increased participant fatigue due to delay in the onset of the target stimulus (here: the time when target vehicle became just audible) [108]. Reduced expectations and increased fatigue together caused decrease in participants' attention and response time, thereby the car was detected slower as its arrival time increased in a particular experimental condition.

Thus, conventional listening tests that use fixed vehicle arrival time may bias the vehicle detection results. Varying the arrival time makes the pedestrian-vehicle interactions more realistic, thus increasing ecological validity of the evaluation experiment. However, the results must be analysed whilst accounting for its effect. This could be achieved by including the target vehicle's arrival time as an independent variable in the experimental design of vehicle detection tests.

5.5.2.2. Understanding and improving methods for subjective evaluation of vehicle sound quality:

It was found that the target EV sounded significantly less powerful with increase in vehicle arrival time. However, its effect size is too small to draw any conclusions from this. It was also found that participants evaluated the target EV as more powerful when approaching from the right.

Sound quality research shows strong correlations between the evaluation of powerfulness and the loudness level of the sound [26]. In this study, the reported loudness level is of the sound emitted and measured at the front speakers. However, the actual sound heard at the pedestrian's position would have been louder when the car approached from the right than from the left. This is because in the experimental design the distance between the target car and the pedestrian's position was shorter when the car approached from the pedestrian's right hand side, as it was moving on a lane nearer to the pedestrian (Figure 5.3). Given the existing loudness-powerfulness relationships [26], this would explain why participants perceived the car sound approaching from the right as more powerful. This result could be further explained by a separate psychoacoustic analysis of target car's sound as heard at the pedestrian's position, for both directions of car's approach and including other metrics not commonly used in automotive sound quality research. Such detailed psychoacoustic analysis and investigation is beyond the scope of this research.

The above results and discussion suggest that conventional listening tests that use fixed vehicle approach direction may bias the results of emotional evaluation of vehicle sounds. Varying the vehicle approach direction makes the pedestrian-vehicle interactions more realistic, thus increasing ecological validity of the evaluation experiment. However, the results must be analysed whilst accounting for the effect of target vehicle's approach direction and distance. To achieve this, the target vehicle's direction of approach and distance of its travel path from the pedestrian's position should be included as independent variables in the experimental design of vehicle sound quality evaluation methods.

Evaluation of pleasantness of the car was not affected by the arrival time or the direction of car's approach. However, no particular inferences can be drawn from it as many participants were confused about using "pleasant" as an attribute for evaluating an electric car based on a sound that is meant to warn pedestrians of its approach. This also explains the significant differences found among the participants' evaluation of the target car's pleasantness depending on the sound emitted.

The semantic "pleasant" is traditionally used for assessing a combustion engine vehicle based on its sounds [26], [28], [56], [57]. The new sounds for electric vehicles are being developed to alert the pedestrians of the vehicle's approach. Therefore, participants could have evaluated the target car while associating its sounds as a warning sound, such as a horn or alarm, rather than a sound that is intrinsic to the car as in a combustion engine vehicle. Thus, they were unable to relate the word 'pleasant' to such a car. It is expected that a reframing of the study to put an emphasis on safety or on the vehicle brand from a potential consumer perspective may avoid confusion regarding the use of the semantic 'pleasant'.

Moreover, participants may also not be finding the use of semantic “pleasant” usual in this particular study due to result of the unrealistic/unrecognisable sounds being used. More representative sounds in future studies would further help in ending the confusion regarding the use of semantic ‘pleasant’ for an (H)EV sound. Furthermore, more semantics may be necessary when trying to compare safety and brand in the same study.

5.5.2.3. Improving the assessment criteria of vehicle exterior sound quality evaluations:

Interestingly vehicle’s detection time and subjective evaluation of its sound quality (using powerfulness and pleasantness dimensions) were not correlated. Thus, sounds with similar detection time could be evaluated differently in the perceptual sound quality dimensions. This supports the assertion made in chapter 2 (section 2.4) that ensuring pedestrians’ safety (assessed via detection rate), and reinforcing the impressions of the vehicle brand (assessed via evaluations on automotive sound quality dimensions of powerful and pleasant) are contrasting issues for future (H)EV sounds. However, they do not need to be competing issues, as a positively emotionally evaluated sound could also be a sound that is detected rapidly. Thus, the existing vehicle exterior sound quality evaluation methods could be improved by assessing the sounds’ for detectability along with the standard sound quality attributes.

5.5.3. Scope for improving methodology-v1

In the light of these results and discussions, particularly section 5.5.2, the methodology-v1 could be improved by using more representative (H)EV sounds as candidates for evaluation. It could be further enhanced by adding measures to subjectively evaluate 'detectability' and 'recognisability as a vehicle' of the target (H)EV sounds. Moreover, the vehicle's arrival time, and the vehicle's direction and distance of approach should be included as independent variables in the experimental design.

5.6. Summary

This chapter describes study 2 as a successful application of methodology-v1 to a pedestrian interacting with an EV in a traffic scenario critical to pedestrians' safety (T-junction). Overall, the study 2 achieved the objective III of this research project by demonstrating the reliability, control and ecological validity of methodology-v1. The results further confirmed that the variations in the target vehicle's arrival time, its direction and thus distance from the pedestrian's position does affect the pedestrians' detection rate and emotional evaluations of the vehicle sounds respectively. Variations of these factors help achieve more ecologically valid scenarios. The results and participants' feedback further confirmed that the introduction of real-life ambient sounds in an evaluation experiment may confuse participants during vehicle detection. The vehicle detection task could be made more representative of real-life by allowing a continuous evaluation of the detectability of the vehicle. This could be through an option of re-recording the detection time in case of mistakes in previous detections and using a subjective scale to evaluate "detectability" of the vehicle sounds. Recognisability of the candidate sounds as a vehicle was identified as an important parameter for evaluation.

Methodology-v1 is an improvement over conventional laboratory listening and on-road evaluation methods, as it presents a more realistic context along with better experimental control and ecological validity. Further, methodology-v1 achieves a more holistic evaluation than conventional methods by evaluating the vehicle sounds’ detection rate to assess pedestrians’ safety as well as emotional evaluations to assess pedestrians’ impressions of the vehicle brand. The proposed methodology was free from any expectancy bias present in conventional evaluation methods that use fixed arrival time and direction of the target vehicle.

Chapter 6: Externally Validating Methodology-v2

6.1. Introduction

The results and feedback from study 2 suggest that methodology-v1 could be further improved by including the assessment of “recognisability” and “detectability” of the (H)EV sounds. Moreover, the target vehicle’s arrival time could be an independent variable of the experiment as it can affect the pedestrian’s detection rate of the vehicle. This chapter describes a new and improved version of the methodology, namely “**methodology-v2**” (version 2 of the methodology) and applies it into another evaluation experiment with a scenario of a pedestrian interacting with an EV in a residential road junction.

Any experimental methodology is only effective if its results generalise to the real world. This is one of the long debated, yet unanswered question in the literature on virtual environments [109]. This research project is trying to develop a method that is ecologically and externally valid. Therefore, this chapter aims at testing external validity of the methodology-v2. The primary objective is to determine if, the methodology enables participants to think, act and react in the same way as a pedestrian evaluating EVs emitting sounds in a real-world environment. Moreover, the study also aims to verify if varying the vehicle’s arrival time affects the pedestrians' evaluation. For this purpose, the study constitutes experiments conducted in two environments, the real-world and virtual-world, using the same methods, stimuli, and participants. Finally, the study compares aspects such as the duration, implementation, reliability and control of experiments in a virtual-world with the real-world. The following sections describe the updated methodology, a literature review of on-road methods for data collection. This is followed by the experiment protocol, results and discussions [110], [111].

6.2. Methodology-v2

The methodology-v2 proposes evaluating (H)EV exterior sounds through an experimental approach that assesses the following aspects:

I. Pedestrians' safety using the following measures:
   a. How quickly is the approach of an (H)EV detected by the pedestrians using its exterior sounds ("**detection rate**")?
   b. How "**recognisable as a vehicle**" do pedestrians find the sound of the (H)EV?
   c. How "**detectable**" do pedestrians find the sound of the (H)EV?

II. Reinforcement of the vehicle brand image using the following measures:
   a. How "**powerful**" is the (H)EV perceived based on its exterior sounds?
   b. How "**pleasant**" is the (H)EV perceived based on its exterior sounds?

The methodology-v2 also proposes the following experimental guidelines for evaluating (H)EV exterior sounds:

I. Use of an **immersive virtual environment(s)** (VEs) to provide the context of a real life pedestrian-vehicle interaction(s) through

a. Traffic scenario(s) that are critical to pedestrians' safety (e.g. electric car moving at low speeds in parking lots, T-junctions, and crossroads)

b. Ambient sounds that represent real life urban environments

II. Candidate target (H)EV sounds should be representative of manufacturer's requirements and also satisfy the legislative guidelines.

III. Detection time measurement method should have options for recording many instances of detections.

IV. The target (H)EV's direction of approach and time of arrival at the pedestrian's position from the beginning of an experimental condition should be an independent variable and manipulated throughout the experiment.

V. The methodology should follow the principles of experimental design:

a. Randomizing the order of presentation of the experimental conditions to control for sequence effects.

b. Using valid and reliable scales such as semantic differential, for subjective evaluation of sounds.

Figure 6.1 shows a flowchart that summarises the elements of methodology-v2.

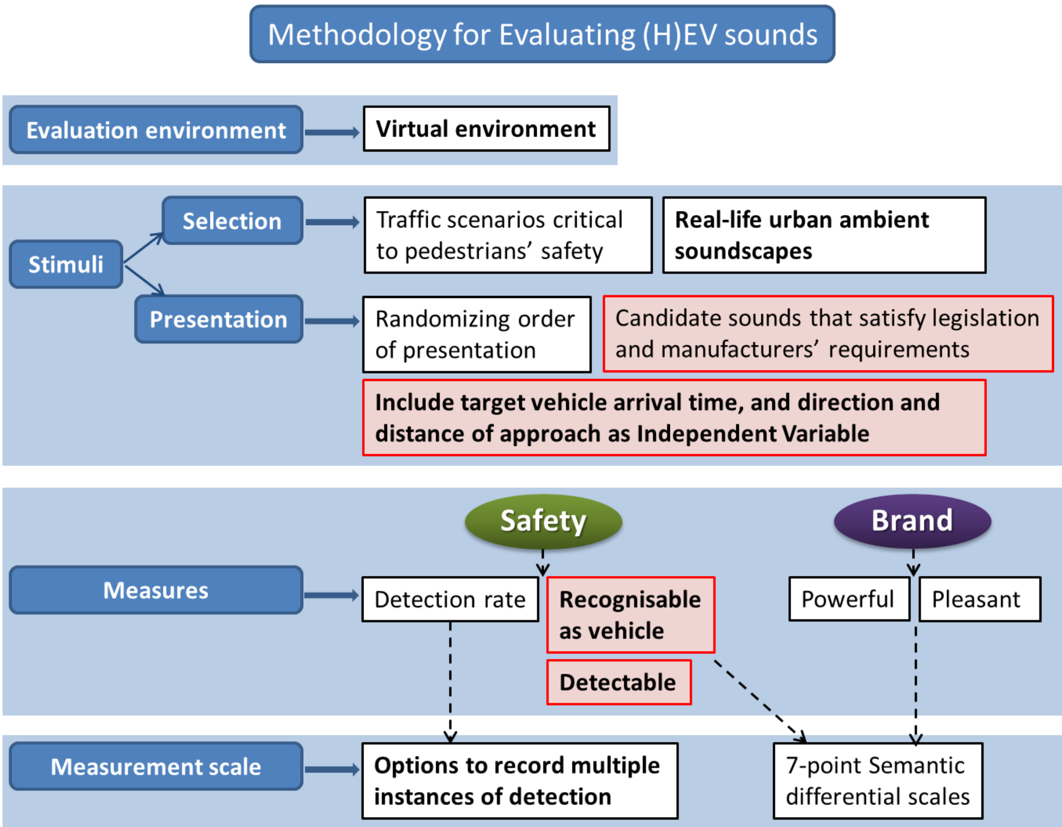


Figure 6.1 Methodology-v2. Here, red blocks denote the changes made to methodology-v1. The bold writings denote the novel approach not found in existing methodologies.

6.3. Measuring Detection Rate in the Real-world

An important concern with the current real world vehicle sounds' detection tests is on how to accurately measure detection rate of the target vehicle. Usually the rate of detecting the vehicle is assessed through measures such as detection distance/time (see 2.6.3.1). Currently, all real world detection studies have limitations in implementing an accurate vehicle-detection rate-measurement-method, as it involves a trade-off between accuracy, cost, feasibility, and installation issues. In this research project, the measurement method for VEs uses an ESS-linked evaluation interface that balances feasibility, accuracy, and cost.

However, other real-world detection studies have primarily used the inaccurate, but economical, methods such as video recordings of the experiment with road markings to estimate the detection distance [31], [32], [35]. More accurate methods such as monitoring the vehicle's position with photoelectric sensors, marking instances of detection using push buttons, and storing the data in a synchronized data acquisition software, are relatively costly and difficult to implement [31]. These methods could have their own errors and problems.

Given the limitations in terms of resources and time, the real world vehicle-detection rate-measurement-method for this study was required to be economical, easy to implement and provide sufficient accuracy. The method also needed to allow recording the instances of vehicle detection as many times as possible as this is an essential part of the presented methodology. Therefore, it was decided to binaurally record sounds during every real world experimental session and the participants be given a sound emitting buzzer to indicate detection. All instances of the vehicle detection could then easily be obtained using the method of time stamping by listening to the binaural recording.

6.4. Study 3: Objectives and Hypotheses

The study had the following objectives:

I. To externally validate methodology-v2 by determining if it accurately predicts pedestrians' evaluation of (H)EV sounds in the real-world.

II. To compare the duration, implementation, reliability and control of the methodology-v2 to the real-world (on-road) evaluation approach.

Similar to study 2, this study also continued testing the following hypotheses:

I. **Hypothesis 1:** Pedestrians' evaluation of vehicle exterior sounds is affected by the change in the vehicle's arrival time.

a. **Hypothesis 1a:** Pedestrians' rate of detecting a vehicle based on its exterior sounds is affected by the change in the vehicle's arrival time.

b. **Hypothesis 1b:** Pedestrians' perceptual evaluation of subjective attributes of a vehicle exterior sound quality is affected by the change in the vehicle's arrival time.

6.5. Study 3: Experiments

6.5.1. Participants

The participants were recruited from the study population set for this research (see 3.4.1). The study was designed for repeated measures ANOVA. Based on a 2x2x3 repeated measures ANOVA design, a minimum sample size of n=12, was required for a minimum statistical power of 0.8 [82] and type I error probability, $\alpha= 0.05$, with a medium effect size, $f= 0.25$ [82]. This was calculated using Software G*Power 3.1.7 [81]. The experiment used 14 experimental conditions (see 6.5.3 and 6.5.5), therefore a sample size of n=14, was required to ensure a complete counterbalancing of the presentation order of the experimental conditions [79].

The final data was collected from 14 participants whose general characteristics are summarised in Figure 6.2. Participants were 10 males and 4 females with the modal age group of 26-35 years, comprising the staff and students from the University of Warwick and two external sound quality researchers. Participants were evenly distributed based on having or not having experienced a VE before (n=7, 7) and having or not having experienced a listening evaluation before (n=8, 6).

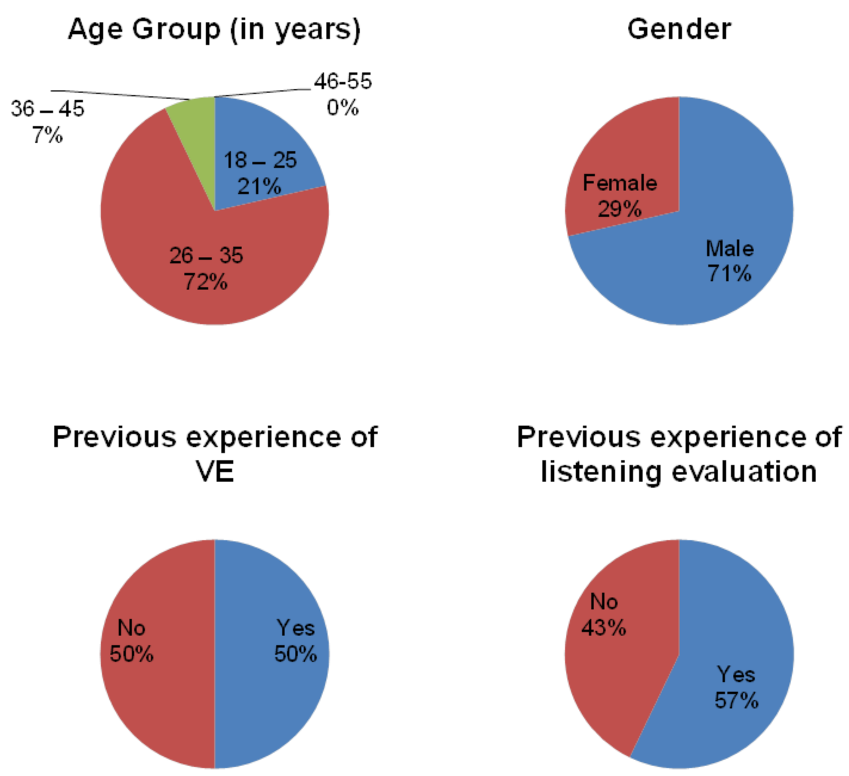


Figure 6.2 A summary of the general characteristics of the participants recruited for study 3.

6.5.2. Evaluation environment

6.5.2.1. Real-world:

Participants listened to car sounds while standing at a real world road junction (see Figure 6.3) within a secured residential area at the University of Warwick campus. The researcher stood next to the participant in order to coordinate the experiment. The target EV emitted different sounds of which SPL and character was controlled using VSound software developed by Brüel and Kjær. The details of the equipment set-up for real-world environment are described in section 3.5.4.

6.5.2.2. Virtual-world:

A virtual-world of a residential road junction that was similar in layout to the junction in the real-world environment was created using the Soundroom-ESS setup (see 3.5.1 to 3.5.3). Overall, this environment was designed to facilitate participants to experience vehicles as if they were standing at a real-world junction (Figure 6.4).

Figure 6.3 The real-world evaluation environment in study 3.

Figure 6.4 The virtual-world evaluation environment in study 3.

6.5.3. Stimuli

Along the lines of previous research studies as well as studies 1 and 2 of this research project, the visual and auditory stimuli for this study were chosen to include one of the many critical scenarios of pedestrian-vehicle interactions. This is because these scenarios being critical to pedestrians' safety require the use of additional sounds from (H)EVs and also provide more relevant context.

6.5.3.1. Visual stimuli:

The visual stimuli are described below as a combination of the experiment location (real-world location or ESS virtual-town location), the pedestrian's manoeuvre, and the target vehicle's manoeuvre.

Experiment location: A private residential road junction surrounded by residence buildings, parks and trees (see Figure 6.3 to Figure 6.5). Figure 6.5 shows the schematic of the experiment location.

Pedestrian's manoeuvre: The participant experienced himself/herself as a pedestrian standing on the pavement of the residential road junction, as represented by position "A" of in Figure 6.5. Figure 6.3 and Figure 6.4 show the visuals as seen by the participant in the real-world and the virtual-world respectively.

Target vehicle's manoeuvre: An electric car started from one of two different starting positions ("S1" and "S2" in Figure 6.5) situated behind the pedestrian on the adjacent parallel road, emitting a sound from its speakers, and travelled at 12 mph (19.3 kph). Therefore, the car arrived at the junction 21s or 29.5s from the beginning of a particular experimental condition thus setting the two arrival time conditions.

6.5.3.2. Auditory stimuli:

Three sounds, denoted as sound 1, sound 2 and sound 3, from an electric car manufacturer were used as the three auditory conditions. The sounds did not have as much variety as the sounds used in study 2. Table 6.1 and 6.2 shows the subjective and key objective metrics of these sounds. The SPL of these sounds was fixed between 57 – 59 dB(A) to comply with the recommended SPL by the AVAS guidelines and FMVSS guidelines [21], [24]. To comply with the legislation, these sounds were broadband with at least 1 signal in the range 160 – 5000 Hz and did not contain siren, horn, chime, bell, alarm, animal, insect or melodious sounds. The total exterior sound of the target EV comprised mainly of the EV's tire-road interaction sound and the additional sound emitted from its speakers whose level, modulation frequency and pitch varied with speed.

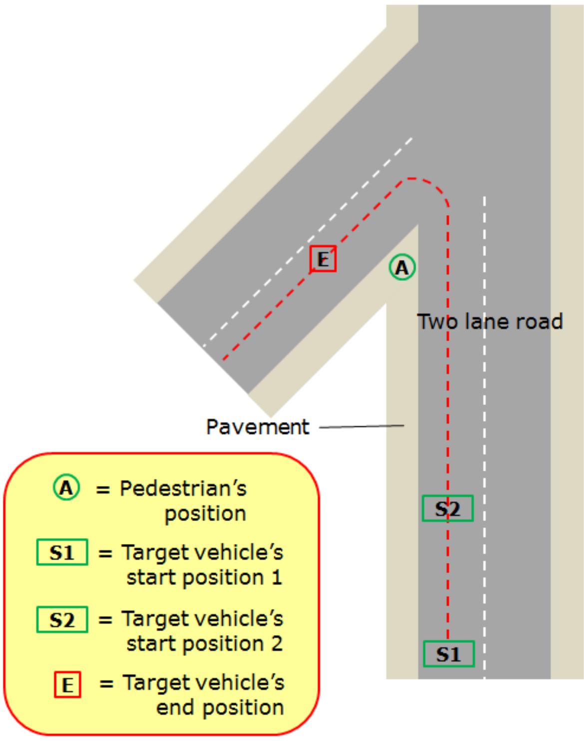


Figure 6.5 Schematic of the visual scenario for study 3. Here, red dotted lines indicate target vehicle's manoeuvre.

In the real-world environment, participants were exposed to the ambient soundscape of the experiment's location. The ambient soundscape comprised of wind, occasional birdsong, geese calling, and distant traffic and construction sounds. The ambient soundscape and sounds of the approaching EV for every participant were binaurally recorded during the real-world experimental conditions. The researcher recorded the sounds using Brüel & Kjær Sonoscout NVH Recorder -

Type 3663 (see Figure 6.3). Ambient soundscape recordings were reproduced at the same SPL ($dB(A)_{eq}$) in the virtual-world environment, to match with the corresponding participant and experimental condition during the real-world experiment.

Table 6.1 and Table 6.2 show the subjective description and key metrics respectively of the sounds 1 to 3 that were used as target car sounds. Since, the number of ambient soundscape recordings were large (7 sounds for every 14 participants = 98 sounds) the equivalent SPL for these are shown in Appendix 7.

Table 6.1 Subjective description of the target car sounds i.e. sound 1 to sound 3 used in study 3.

Sound ID	Subjective description
Sound 1	Sounds consisted of harmonics with fundamental frequency of 300 Hz
Sound 2	Sounds consisted of harmonics with fundamental frequency of 300 Hz, superimposed with a sinusoidal wave at 2nd harmonic and a sawtooth wave at 3rd harmonic
Sound 3	Sounds consisted of harmonics with fundamental frequency of 300 Hz, superimposed with a sinusoidal wave at 2nd harmonic and an irregular wave at 3rd harmonic

Table 6.2 Key psychoacoustic metrics of the target car sounds i.e. sound 1 to sound 3 used in study 3.

Sound	SPL (dB(A))	Loudness (sones)	Sharpness (acum)	Roughness (asper)
Sound 1	57	4.91	0.437	0.045
Sound 2	59	6.48	0.795	0.000
Sound 3	58	5.64	0.517	0.102

6.5.4. Measures

6.5.4.1. Assessing Pedestrians' safety:

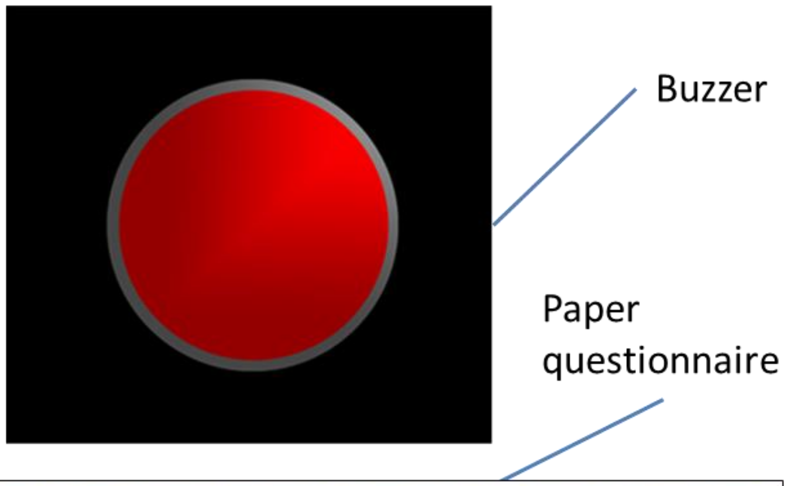
Detection rate: The rate at which pedestrians detected the target EV was measured using the measure most used in the research involving 'quiet' vehicles [10], [31], namely "**detection distance**". "Detection distance" is defined here as: "*the distance of the target vehicle from the pedestrian's position at the instance the pedestrian indicates detection*". The time difference between the instances of vehicle detection and vehicle's arrival at the junction (time-to-vehicle-arrival) was multiplied with the vehicle's speed, 12 mph (19.3 kph), to calculate the detection distance.

In the real-world environment, the participant was asked to press a buzzer on an electronic touch screen tablet interface (Figure 6.6) as soon as (s)he heard or saw the target EV. Following this, the researcher pressed a buzzer as soon as the EV arrived at the junction. These buzzer sounds were heard on the binaural recordings for every experiment and were used to calculate detection distance.

The virtual-world environment used a touch screen ESS-linked evaluation interface and synchronized with the experiment condition. The interface had a 7-point semantic scale: "not heard – heard" (Figure 6.7) that the participant was asked to slide as soon as (s)he heard or saw the target EV. The interface recorded the time of every instance the scale was moved. If the participant later thought (s)he had incorrectly perceived hearing the car or pressed the buzzer/ moved the scale mistakenly, (s)he was instructed to do this again when the participant thought (s)he started hearing the EV. The detection time was calculated from the last instance the participant pressed the buzzer/ moved the "not heard – heard" scale.

Recognisability: The pedestrian's evaluation of the recognisability of the target EV sound as a vehicle was collected using a 7-point scale of "not recognisable as vehicle – recognisable as vehicle". In the real-world environment, a paper questionnaire contained the scale (Figure 6.6). In the virtual-world environment, the participant recorded the ratings by moving the scale on the ESS evaluation interface to the appropriate value (Figure 6.7).

Detectability: The pedestrian's evaluation of the detectability of the target EV sound was collected using a 7-point "not detectable – detectable" scale on the paper questionnaire in the real-world, and the ESS interface in the virtual-world environment.



Based on your listening to the car's sound, evaluate the car on the following attributes on a scale of 1 to 7.

Car 1:

Not recognisable as vehicle	1	2	3	4	5	6	7	Recognisable as vehicle
Not detectable	1	2	3	4	5	6	7	Detectable
Weak	1	2	3	4	5	6	7	Powerful
Unpleasant	1	2	3	4	5	6	7	Pleasant

Figure 6.6 Data collection in the real-world environment in study 3.

Figure 6.7 Data collection in the virtual-world environment in study 3.

6.5.4.2. Assessing impressions of the vehicle brand:

"**Powerfulness**" and "**pleasantness**" are well-established emotional dimensions of vehicle sound quality [28], [56], [57] that could help understand a listeners' impression of the vehicle brand. In study 2, participants found pleasantness an unusual semantic term for describing (H)EV sounds. Unlike study 2 that used non-vehicle like tones and melodies, this study used more representative manufacturer sounds for the target car. Moreover, participants were specifically instructed to evaluate the vehicle brand based on its exterior sounds (section 6.5.6). Thus, this study reused 'pleasantness' to check if it becomes an appropriate semantic for evaluating (H)EV sounds after implementing the above changes. Powerfulness and pleasantness of the EV based on listening to its sound was evaluated using 7-

point scales of “weak – powerful” and “unpleasant – pleasant” on the paper questionnaire in the real-world, and on the ESS interface in the virtual-world.

6.5.4.3. Participants’ feedback:

At the end of experiment in each environmental condition, on a paper questionnaire, participants rated on a scale of 1 to 7 the comfort and enjoyment of the overall experiment. There was also an optional question to please provide feedback or suggestions, if any, to improve this experiment.

6.5.5. Experimental design

A repeated measures design was used with a) environment (real-world and virtual-world), b) target car’s arrival time (21s and 29.5s) and c) target car’s sound (sound 1, 2, and 3) as independent variables. Thus, a 2X2X3 repeated measures design gave 12 different experimental conditions. Within each environment, (real-world and virtual-world) one experimental condition, namely target car emitting sound 1 and arriving at 29.5s, was repeated to check external reliability of the experiment. Therefore, each participant was exposed to 14 experimental conditions (7 experimental conditions per environment). Exposure to a fixed sequence of experimental conditions may bias the results due to practice effects (participants become more experienced and better at the task as the experiment proceeds) [79], and fatigue effects (participants get tired as the experiment proceeds) [79]. The same presentation order was maintained for each participant during the real-world and the virtual-world environment but order effects were controlled for using 7X7 balanced Latin square [79]. Appendix 8 shows the presentation sequence of the experimental conditions for every participant.

6.5.6. Procedure

Before the experiment, a written informed consent was obtained from the participant. Participant reported his/her age, gender and if they had experienced a VE or listening evaluation previously. The experiment was then performed on each participant one at a time in the following manner:

I. Participant stood on the residential junction during the real-world experiment (position “A”, Figure 6.5) or sat on the listening position in the soundroom (see 3.5.3) during the virtual-world experiment.

II. If and only if the participant self-reported as feeling “well” (s)he was allowed to proceed.

III. Participant was briefed about the experiment.

IV. Participant was instructed to first detect the car aurally or visually (whichever was first). Then, they were instructed to evaluate how detectable and recognisable the target EV sounds were, and how powerful and pleasant the target EV sounded.

V. Participant was exposed to the experimental conditions and (s)he completed the task.

VI. (S)he was thanked, debriefed and feedback was collected.

The experiment in the real-world environment was completed first, followed by a two-month gap before completing the experiment in the virtual-world environment. The two-month gap allowed sufficient time for participants to forget the stimuli. In the real-world environment, the researcher and the driver communicated via Bluetooth and confirmed that no other passing vehicles were visible nearby. The driver then selected a sound (1, 2 or 3) corresponding to the experimental condition from a VSound laptop (see 3.5.4), began driving and reached the desired 12 mph (19.3 kph) speed. As soon as the front of the car approached the corresponding starting position (S1 or S2, Figure 6.5) the driver communicated this to the researcher. The researcher then immediately announced to the participant that the experimental condition had begun. In the virtual-world environment, these experimental conditions were synchronised using ESS.

6.6. Study 3: Results

The data satisfied all assumptions of repeated-measures-ANOVA (see Appendix 9).

6.6.1. External reliability

Repeated-measures-ANOVA found no significant differences in the detection rate, recognisability, detectability and powerfulness upon repeating an experimental condition within the real-world and the virtual-world environment (Table 6.3). Although pleasantness ratings had no significant difference upon repeating the experimental condition in the real-world, they significantly differed for the virtual-world. This was regarded an experimental anomaly. As only one of ten results significantly differed, overall both experiments were considered reliable. So, the mean data of the repeated experimental conditions were used for further analysis.

Table 6.3 Effect of repeating an experimental condition within each environment on pedestrians' evaluation of EV sounds in study 3.

Environment	Measure	Repetition 1		Repetition 2		F	p	Partial η^2
		Mean	SE	Mean	SE			
Real-world	Detection distance (m)	49.10	6.49	48.51	6.33	.007	.933	.001
	Recognisability	4.14	0.36	4.79	0.38	3.545	.082	.214
	Detectability	4.00	0.44	4.43	0.44	1.721	.212	.117
	Powerfulness	3.00	0.38	3.43	0.37	3.545	.082	.214
	Pleasantness	4.71	0.34	4.93	0.29	.511	.487	.038
Virtual-world	Detection distance (m)	28.01	6.89	24.80	8.10	.191	.669	.014
	Recognisability	3.71	0.44	4.36	0.53	1.918	.189	.129
	Detectability	3.71	0.47	3.86	0.47	.134	.720	.010
	Powerfulness	3.29	0.37	3.71	0.35	1.219	.290	.086
	Pleasantness	4.07	0.32	4.86	0.25	5.026	.043*	.279

Here, df = 1, df_{error} = 13, and $^*p$<.05.

6.6.2. Effect of environment

Repeated-measures-ANOVA was performed with experiment environment, target car's arrival time and target car's sound as independent variables and the detection distance and ratings of recognisability, detectability, powerfulness and pleasantness as dependent variable. Table 6.4 shows these results.

Table 6.4 Effect of environment, arrival time and target car's sound on the pedestrians' evaluation of EV sounds in study 3.

Factor	Level	Statistics	Measure				
			Detection rate (m)	Recognis -ability	Detect-ability	Powerful -ness	Pleasant -ness
Evaluation environment	Real-world	Mean	47.38	4.49	.42	3.51	4.7
		SE	2.46	0.15	.17	0.14	0.14
	Virtual -world	Mean	31.96	3.78	.2	3.58	3.92
		SE	3.07	0.17	.14	0.14	0.15
	—	F	11.427	7.069	.481	0.185	3.693
		p	.005**	.020*	.5	0.674	0.077
		Partial η^2	0.468	0.352	.036	0.014	0.221
Arrival time	21 s	Mean	43.66	4.17	.27	3.5	4.26
		SE	3.13	0.17	0.16	0.15	0.14
	29.5 s	Mean	35.69	4.11	4.35	3.6	4.36
		SE	2.59	0.16	0.16	0.14	0.15
	—	F	7.126	0.187	0.201	0.556	0.229
		p	.019*	0.673	0.661	0.469	0.64
		Partial η^2	0.354	0.014	0.015	0.041	0.017
Target car's sound	Sound 1	Mean	36.96	4.41	4.05	3.48	4.55
		SE	3.20	0.20	0.20	0.17	0.15
	Sound 2	Mean	46.49	3.89	4.45	3.57	4.21
		SE	4.30	0.19	0.18	0.17	0.20
	Sound 3	Mean	35.57	4.11	4.43	3.59	4.16
		SE	2.87	0.20	0.19	0.18	0.19
	—	F	7.40	3.54	1.46	0.11	1.65
		P	0.01^{*}	0.04^{*}	0.25	0.88	0.22
		Partial η^2	0.36	0.19	0.10	0.01	0.11

Here, for environment and arrival time: df = 1, df_{error} = 13; for target car sound: df = 2, df_{error} = 26; and $^{*}p<.05$, $^{**}p<.01$.

Participants detected the target car at significantly larger distances (faster detection) and also found the target sounds significantly more ‘recognisable as a vehicle’ in the real-world than in the virtual-world. No significant differences were found between the real-world and the virtual-world environment in participants’ detectability ratings of the target car’s sound nor the powerfulness and pleasantness of the target car.

The significant differences in the detection distances and recognisability were further explored. The difference between the detection distances in the real-world and virtual-world (detection $\text{distance}_{\text{real-world}}$ – detection $\text{distance}_{\text{virtual-world}}$) ranged from -89.05 m to 72.74 m and was inconsistent throughout the experimental conditions, mean Pearson’s correlation coefficient, r =.14, p>.05 [112]. Similarly, the difference between the recognisability in the real-world and virtual-world ($\text{recognisability}_{\text{real-world}}$ – $\text{recognisability}_{\text{virtual-world}}$) ranged from -4 to 5 and was inconsistent, mean Pearson’s correlation coefficient, r =.16, p>.05 [112]. A comparison of the ranking of sounds based on detection distances showed that in both environments sound 2 was detected the fastest compared to sound 1 and sound 3 (Figure 6.8). The ranking of sounds based on being recognisable as vehicle were same for both environments, sound 1 being most recognisable followed by sound 3, and sound 2 being the least recognisable (Figure 6.9).

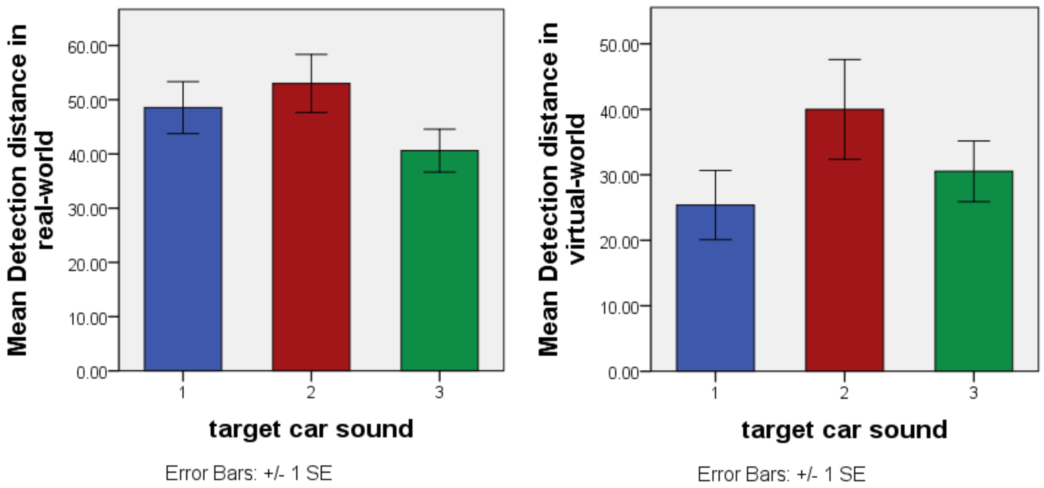


Figure 6.8 The target sounds' ranking based on the target car's detection distance in study 3. Note: consistent trend in detection rates of sounds.

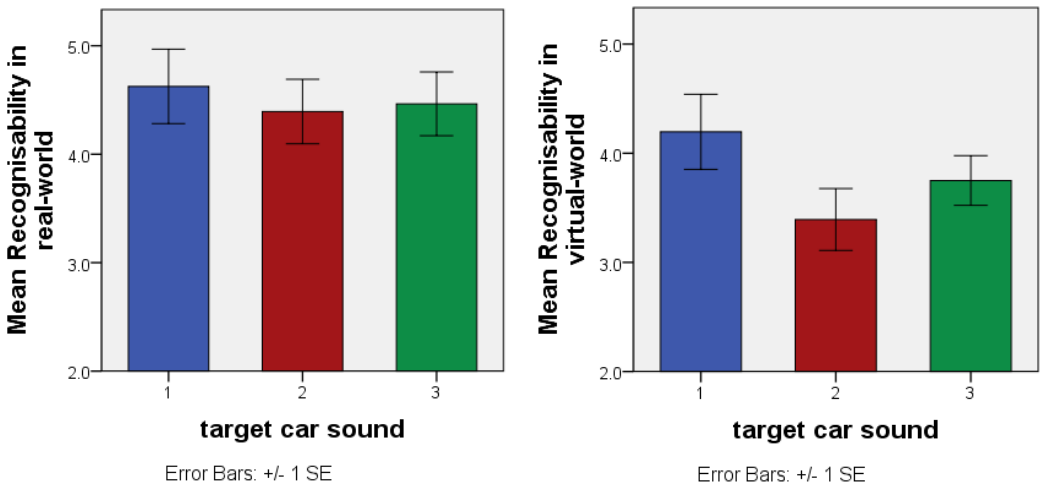


Figure 6.9 The target sounds' ranking based on their recognisability as a vehicle in study 3. Note: consistent trend in detection rates of sounds.

6.6.3. Effect of target EV's arrival time

The participants detected the target car at significantly larger distances (faster detection) when the target car arrived at 21 seconds compared to 29.5 seconds (Table 6.4). Thus, the car was detected faster when it arrived sooner and vice versa. However, the target car's arrival time had no significant effect on participant's subjective rating of the target car sounds' recognisability, detectability;

or target car's powerfulness and pleasantness. This finding has continued to support hypothesis 1a of this study, but rejected hypothesis 1b.

6.6.4. Effect of target EV's exterior sounds

Overall, the target car's exterior sounds significantly differed in the distances at which they were detected by the pedestrians and how recognisable as a vehicle they were perceived (Table 6.4). However, there was no significant difference in their detectability, and how powerful and pleasant was the overall vehicle perceived.

Paired contrasts revealed that overall (real-world and virtual-world combined) sound 2 was detected significantly faster than sound 1 $F(1,13)= 9.482$, $p<.05$, and sound 3 $F(1,13)= 8.571$, $p<.05$. There was no significant difference in detection rate of sound 1 and sound 3, $F(1,13)= .375$, $p>.05$.

Similarly, paired contrasts found that overall (real-world and virtual-world combined) sound 1 was significantly more recognisable than sound 2 $F(1,13)= 5.464$, $p<.05$. However, there was no significant difference in recognisability of sound 2 and sound 3, $F(1,13)= .807$, $p>.05$ and sound 1 and sound 3, $F(1,13)= 2.937$, $p>.05$.

6.6.5. Correlation between measures

Table 6.5 shows the Pearson correlation coefficients between the mean values of the measures used in this study [113]. Only recognisability and pleasantness has significant strong positive correlation. Among insignificant correlation, recognisability and detection rate, and detectability and powerfulness were moderately positively correlated.

Table 6.5 Pearson correlation coefficients (r) between the measures in study 3.

		Mean detection distance	Mean recognis-abiltiy	Mean powerfulness	Mean detectability	Mean pleasantness
Mean recognisabiltiy	r	.449				
	p	.143				
Mean powerfulness	r	-.046	-.136			
	p	.887	.673			
Mean detectability	r	.373	.105	.529		
	p	.232	.745	.077		
Mean pleasantness	r	.416	.693*	-.077	.042	
	p	.179	.013	.813	.897	

*p<.05.

6.6.6. Participants' feedback

Overall, the participants rated both the real-world and the virtual-world environment experiments as very comfortable and enjoyable. On a scale of 1 to 7, the mean comfort levels of the evaluation experience during real-world and the virtual-world were 6.18 and 6.45 respectively. The mean enjoyment levels of real-world and virtual-world experiment were 6.27 and 5.91 respectively. Paired-t tests showed no significant differences in comfort, $t(10)= -1.4$, $p>0.05$, and enjoyment ratings, $t(10)= 1.79$, $p>0.05$, for the real-world and virtual-world experiments.

Participants did not provide any general feedback or suggestion for improving the experimentation method. Unlike study 2, participants in this study did not comment or raise an objection to the use of the semantic "pleasant" for describing the impression of the target EV based on its exterior sounds.

A few participants (n=4) commented that during the real-world experiment some of the target cars (sound 1) were very quiet and they could hear the tyres before actually hearing the sound emitted from the speakers on the EV. Therefore, they rated those sounds only based on its tyre noise. During both real-world and virtual-world environment experiments some participants (n=3) commented that some sounds (sound 3) were heard much earlier but at first they did not recognize them as emanating from an approaching vehicle so they pressed the detected button/scale much later after making sure it was a vehicle. They also mentioned that they, as pedestrians, may learn to recognise these sounds as a vehicle over time.

6.7. Study 3: Discussions

External validity is one of the most fundamental, debated and yet unanswered topic in the literature on simulators and VEs [109]. This study tested external validity of methodology-v2 by determining if the methodology enables participants to think, act and react in the same way as a pedestrian evaluating (H)EVs emitting sounds in the real-world. Another objective was to make a methodological comparison of methodology-v2 with a real world experiment.

It was found that participants evaluated EV sounds whilst being pedestrians in a virtual-world environment in a similar way as when they evaluated the sounds in a real-world environment. However, in the virtual-world environment participants found it significantly harder to recognise EV sounds and took longer to detect them than in the real world. However, they did detect and recognise these sounds in a similar order as in the real-world environment. The results therefore partly support methodology-v2 as an equivalent to real-world testing conditions for evaluating (H)EV exterior sounds. Study 2 of this research found that vehicle’s arrival time can affect the pedestrian's detection rate and this study further confirms this result. It highlights (H)EV's arrival time as a key methodological aspect that affects pedestrians' detection rate and makes pedestrian-vehicle interactions more realistic thus providing a better context. Hence, target EV's arrival time should be manipulated in future experiments.

6.7.1. Testing external validity of methodology-v2

Participants' evaluation of the detectability of the target car's sound and the powerfulness and pleasantness of the target car in a virtual-world environment did not significantly differ to a comparable scenario in a real-world environment. This suggests participants were responding similarly in the virtual world as in the real world for detectability and emotional evaluation.

Recognisability of the EV sounds, however, was significantly higher in the real-world than in the virtual-world environment. This means that the same simulated sounds seem more recognisable in the real-world than in a virtual-world. Another explanation is that by the time participants made their recognisability ratings they had seen a real EV emitting these sounds in the real-world thus increasing their association of these sounds to a vehicle. Additionally, a person without an automotive background is unlikely to know all of the numerous automotive sounds in existence and so unable to rate a set of sounds on an absolute measurement scale. As a result, the process of evaluating automotive sound quality on perceptual attributes is essentially a process of providing relative ratings to a set of candidate vehicle sounds [58]. Similarly, in this study, a participant provides relative scores on the perceptual attributes, based on the vehicle sounds they have been exposed to previously, or during the experiment. Therefore, though less important than actual scores of emotional evaluations, the ranked order of sounds being evaluated is valuable information which the virtual-world experiment accurately predicted for recognisability of sounds in the real-world. It is worth noting that this experiment used three acoustically similar sounds (see section 2.3) developed for a single EV brand. On the contrary, many previous studies have used a very diverse set of sounds such as engine, melodious, bell, pure tones and nature sounds [31], [32], [106], or sounds from different brands [33]. With an extremely diverse set of sounds, it is easier for a method to predict their ranked order or ratings in the real world. However, this methodology differentiates and predicts ranked order and ratings of very similar sounds, which further highlights its validity.

Overall, it can be said that experiments conducted in the virtual-world using methodology-v2 will produce results that effectively predict pedestrians' emotional evaluations of vehicle exterior sounds in real-world conditions. However, current evaluation tests of EV sounds [9], [10], [31]–[33], [35], [36], [114] do not combine detection tests with assessing a listener's emotional responses to EV exterior sounds. Including emotional evaluations in EV exterior sound studies will make them similar to the focus of sound quality evaluation tests, usually conducted for interior sounds, in a vehicle's design process [26], [28]–[30], [57], [58]. In that way, this methodology can be directly integrated within automotive industries' vehicle design and development processes.

In this study, the EV was detected at a significantly greater distance by a pedestrian in a real-world scenario than in a comparable virtual-world environment. This suggests that VEs using methodology-v2 are not accurate at representing how fast pedestrians react to and detect a vehicle in the real world. However, in this study there were two potential human-related errors in the real-world condition that were absent in the virtual-world condition and these could have affected the measured values of detection distances. Firstly, in the real-world condition there was the potential for "**operator's manual control error**" [115] if the driver deviated from driving the EV at 12 mph (19.3 kph), and four different drivers were used during the study. If we take the mean detection distance observed as 47.38 m (see table 6.4), then an error of 1 mph (1.61 kph) speed deviation would have caused a detection distance error of 3.95 m. In contrast, in the virtual-world condition the EV was 'driven' by the ESS software at a constant 12 mph (19.3 kph), to ensure the car arrived exactly at one of two 'arrival time' conditions (21s or 29.5s). Secondly, in the real-world condition there was the potential for "**human observer measurement error**" [116] as the driver needed to verbally state when the car crossed a given line (experiment's starting position), and the researcher needed to state when the car had arrived at a given point by pressing a buzzer. Here, an error of 1 s in researcher's or driver's observation would have caused a detection distance error of 5.4 m each. Whilst in the virtual-world, ESS software accurately monitored these two instances thereby eliminating measurement discrepancies.

Both the operator's manual control error and human observer measurement error are by definition random errors [115], [116]. When the differences in the detection distances were analysed it was found that they too are random errors, as they are inconsistent throughout the experimental conditions (low correlation) and bi-directional (negative and positive errors). Thus, the detection distance differences are likely to be caused by random errors such as human-related measurement errors, and/or effect of uncontrolled external factors such as weather, lighting, traffic, etc. Most likely, they are not caused due to a problem in the presented methodology because then the differences would be systematic across all conditions.

Therefore, the study suggests that people react faster and are more aware of a vehicle approaching in the real-world than in the virtual-world. Despite the significant differences in participants' reaction time to an EV approaching in the real and virtual-world environments, the ranked order of EV sounds based on their detection distance was the same in both environments. Thus, the results from the virtual-world environment are still generalizable to the real-world, and thus supports the methodology-v2.

6.7.2. Effect of arrival time on pedestrians' detection rate

Pedestrians took longer to detect the target car, responding at a slower rate when the car arrived later in time. This supports and confirms the relationship between the target car's arrival time and pedestrians' detection rate as already found in study 2 [106]. This implies that the attention level of pedestrians reduced with the passage of time within an experimental condition. In most conventional listening tests, the car sound to be detected is present from the very beginning of the stimulus, and has a fixed arrival time at the pedestrian's spot [9], [10], [38], [114], so after a few trials, participants begin to expect to hear the car straight away. Therefore, participants may pay more attention towards hearing the car at the beginning of an experimental condition. These conventional tests do not represent a real-world pedestrian-vehicle interaction where a car may approach a crossroad/junction at any time. Thus, conventional listening test methods may produce results different from a real-world traffic scenario.

On the other hand, methodology-v2 involves varying the target car's arrival time throughout the experiment, just as it would be in a real-world scenario especially at un-signalised crossroads and junctions. Thus, it enables participants to think, react and pay similar attention as a pedestrian in the real-world who is unsure of the time of a car's approach and his/her expectation will not be as evident. Thus, in real-world situation as also in experiment conducted using methodology-v2, with time a pedestrian's attention may shift from focussing on detecting the target car's sound, to the perception of other stimuli such as, visual and ambient sounds. Reduced expectations and decreased attention may have caused the participants to react slower towards the end of a particular experimental condition. The same is also expected in a real-world scenario. Therefore, varying the target car's arrival time is recommended for future studies.

6.7.3. Virtual-world versus real-world vehicle sounds' evaluation: a methodological comparison

It is usually critiqued that real-world experiments or field studies have much lower reliability compared to a laboratory study [59], [106]. However, this study has resulted in successful protocols for conducting experiments in a virtual-world environment and in the real-world that have significant external reliability. It is also argued that the conventional laboratory automotive listening tests could be monotonous and overall less enjoyable compared to the corresponding real-world evaluations. However, the use of virtual-world environment through methodology-v2 makes the overall laboratory experiment as enjoyable and comfortable as the real-world evaluation.

Experiments in the virtual-world environment were quicker compared to the real-world environment, taking only 8 minutes per participant for completion of the seven experimental conditions. In contrast, in the real-world, the completion of these seven experimental conditions took between 30 to 45 minutes per participant, excluding the time to arrive or leave the experiment site. This was because of the interruptions from other vehicles passing the experiment location and time taken to achieve the car's desired manoeuvre before beginning a new experimental condition. Furthermore, the virtual-world experiments for all 14 participants were completed in one week. In comparison, the real-world experiments took one month to complete because of implementation difficulties. The real-world experiments were cancelled on two occasions due to problems with vehicle charging and tyre puncture, thus causing a ten-day delay. Moreover, one participant's data was not used due to heavy winds that interfered with binaural recording. Initially, it was decided to maintain a low speed condition of 10 mph (16.1 kph) for experiments just as in the previous study [106], [105]. But the pilot study showed that in the real-world drivers found 10 mph difficult to maintain therefore 12 mph (19.3 kph) was chosen for actual experiments with a speed tolerance of ± 1 mph (1.61 kph) (note a digital speed dial was used).

Overall, we can say that methodologically virtual environments seem a preferred alternative to real-world studies as they are quick, easy to implement and provide better experimental control. Additionally, virtual environments allow easy manipulation of factors such as vehicle's arrival time, direction [106], and ambient conditions, which is difficult to achieve in the real-world and also in conventional laboratory listening tests.

6.7.4. Review of methodology-v2

Interestingly, participants' comments reveal that during the evaluation although certain EV exterior sounds (sound 3) were heard much earlier, i.e., were more audible, being less recognizable as a vehicle they were detected much later in time because participants pressed the detection button/scale only after making sure it was a vehicle. This is similar to the real-world traffic scenarios where pedestrians are exposed to many vehicle and non-vehicle based sounds. Here, detecting the target vehicle's sound automatically triggers recognizing the sound as a vehicle. This reasoning explains the fact that a strong positive correlation was found between recognizability and detection distance, r= 0.45, compared to a weak correlation of detectability with recognizability (r=.11) and detection distance (r=.37). Moreover, the pedestrians may learn to recognise these sounds as a vehicle over time. Therefore, methodology-v2 could be revised to combine 'recognisability' and 'detection' as a single measure. This requires simply instructing the participants to detect an approaching "vehicle".

6.8. Summary

This chapter describes study 3 as a successful application of methodology-v2 to a traffic scenario of a residential road junction. Methodology-v2 produces results that accurately predict pedestrians' real world evaluations of the detectability of EV sounds and pedestrians' real-world impression of the powerfulness and pleasantness of the vehicle brand. The results are also generalisable to how recognisable pedestrians find these sounds in the real world. Moreover, methodology-v2 is found to be quicker, more convenient and accurate compared to real world vehicle sounds' evaluation. Thus, overall, study 3 achieved objective IV and V of this research. The methodology varies vehicle's arrival time across the experimental conditions just like in a real world scenario, which may help participants think, respond and pay similar attention as a real-world pedestrian.

Chapter 7: General Discussions

7.1. Introduction

The thesis has already discussed findings from the individual studies in the relevant chapters. This chapter presents a broader discussion of the results and their implications in relation to their contribution towards the overall research question and objectives. Unifying themes across the studies are extracted to reflect on the methodological approach, its strengths and potential limitations. Consequently, methodological guidelines are produced for future (H)EV exterior sound evaluations. Themes are also extracted to interpret the findings in the context of the current knowledge on automotive sound quality and auditory detection theory. Finally, the chapter closes by summarising the knowledge contribution of this research project and the areas for future work.

7.2. Review of the Proposed Methodology for Evaluating (H)EV Exterior Sounds

The research project has proposed and tested a new methodology for evaluating (H)EV exterior sounds that balances experimental control with ecological and external validity. Table 7.1 summarises the advantages and limitations of the final methodology, i.e. methodology-v3, compared to the existing methods of automotive exterior sound quality evaluation. Table 7.1 also provides the reference to the thesis sections that have demonstrated these advantages and limitations. These advantages and limitations are discussed in detail in the following sub-sections.

Table 7.1 Advantages and limitations of methodology-v3 for evaluating (H)EV sounds

Advantages	**Reference sections**
More experimental control than existing on-road automotive sounds' evaluation methods	4.4.3, 4.4.6, 5.3.3, 5.3.5, 5.4.2, 5.5.1.1, 6.5.3, 6.5.5, 6.6.1, 6.7.3
More appropriate context than existing automotive sounds' laboratory listening tests	4.4.2, 4.4.3, 4.5.2, 5.3.2, 5.3.3, 6.5.2.2, 6.5.3
Ecological validity, which is not practiced within the existing methods of automotive exterior sound quality	4.5.2, 5.3.5, 5.5.1.2, 5.5.2.1, 5.5.2.2
External validity, a crucial aspect that is not been proven by existing laboratory evaluation methods	6.6.2, 6.7.1
Limitations	**Reference sections**
Gamepad for navigating the VE is difficult to learn and control. Alternate option: better controller for navigation, non-interactive evaluation	4.5.3.2, 4.5.3.3, 4.6
ESS interface does not have press buttons to indicate vehicle detection. Alternate option: rating scales to record time	5.3.4.1

7.2.1. Advantages

Most on-road studies have a very low degree of experimental control [36], [48]. This may lead to difficulties in manipulating experimental variables and achieving sufficient reliability. The methodology has proposed using VEs for evaluation. Studies 1 to 3 have each demonstrated the ease and degree of control that could be achieved with the technique of VE simulation. Study 2 and study 3 also show that the presented methodology is externally reliable as they found no significant differences in participants' response upon repeating an experimental condition ($p < .05$).

Controlling the ambient soundscape is the greatest challenge in any on-road experiment [31], [36], [48]. The real-world experiment of study 3 showed that fluctuations in ambient soundscape and interference from traffic increased both the duration and timeline of the total experiment. Many implementation precautions were taken to prevent sound from non-experimental vehicles, even then, a similar ambient soundscape could not be achieved for every participant. The proposed methodology is able to overcome this issue. For example, study 1 used two fixed ambient soundscapes for every visual scenario and participant, study 2 maintained the same ambient soundscape for every participant and condition, whereas study 3 used a different pre-determined ambient soundscape for every condition as well as participant.

Additionally, the methodology successfully manipulated target car's arrival time, distance and direction of travel in study 2. Altering these factors increases the experiment's ecological validity. Study 3 showed that the target car's arrival time was difficult to control and alter accurately in the real-world due to "operator's manual control error" [115] or intervention by non-experiment vehicles. Use of VE simulation in the proposed methodology made the altering of target car's arrival time much quicker and easier compared to the corresponding real world experiment (10 minutes compared to 40 minutes). Results from study 3 indicate the possibility of human errors ("human observer measurement error" [116] and "operator's manual control error" [115]) in measuring the target car's detection rate during the real-world experiment. Here, the detection rate was evaluated in terms of detection distance that was calculated using detection time and vehicle speed. The human errors in measuring detection rate could be attributed partly to deviations in the vehicle speed in the real world from the desired 19.3 kph. This further demonstrates that achieving desired constant speed manoeuvres is difficult in the real world, but can be easily achieved in the VE.

Overall, comparing virtual-world and a corresponding real-world experiment in study 3 shows that the presented VE-based methodology achieves a better experimental control that the current real-world (on-road) experiments.

Presence and immersion are widely used to measure simulation fidelity of VEs. Participants experienced moderate level of presence and immersion (score of 4.10 on a scale of 1 to 7) with sufficient degree of involvement/control, naturalness, resolution, and interface quality (scores between 3.50 and 4.50 on a scale of 1 to 7). The participants found the visual and auditory aspects of the VE and the overall VE experience involving (scores of 4.1 and 4.4 on a scale of 1 to 7). These scores are comparable to the presence and immersion scores experienced by participants in other similar VE set-ups found in literature [63], [93], [94]. Thus, overall the VE set-up of this research has sufficient fidelity so that participants feel present and immersed in the traffic scenarios it simulates, which helps establish a more appropriate context. Participants experienced low to no symptoms of simulator sickness in the VE set-up of this research. According to Kennedy et al. (1993) the symptoms found in the present study are low compared to a large number of VE/VR systems studied by them [98]. The total simulator sickness as well as nausea, oculomotor and disorientation (mean scores = 39.74, 28.62, 24.64, and 60.9 respectively) experienced by the participants is comparable to most accepted modern VE systems [95], [96], [99].

A major challenge with most laboratory listening evaluation methods is that they lack appropriate context and ecological validity [106]. This is mainly because the way laboratory listening evaluation experiments are conducted and the context of them make it very different from the way a pedestrian interacts and evaluates with a vehicle sound in real life. Laboratory listening tests involve listening of the target car sounds, usually in the absence of any ambient soundscape or a visual scenario. Moreover, the arrival time, distance of approach and direction of the target car is usually constant throughout the experimental conditions [9], [10], [32]. In a real world, scenario and especially in junctions and turns with no traffic lights a car may approach the pedestrians' intended path of travel from any direction and at any time. That is why a pedestrian is never sure of the target vehicle's arrival and continuously listens for vehicle sounds before crossing. The methodology employs altering the distance, direction and arrival time of the target (H)EV throughout the experimental conditions just like a real world scenario. This enables participants to think, act and pay a similar level of attention as a pedestrian in the real world. Moreover, multiple detections replicate real-world detection process. Using real world ambient soundscapes, relevant traffic visual scenarios, altering vehicle’s manoeuvre and multiple detection facility helps improve experiment’s ecological validity. It is also argued that the conventional laboratory listening tests could be monotonous and overall less enjoyable compared to corresponding real-world evaluations. However, feedback from study 3 indicates that the proposed methodology makes the overall laboratory experiment as enjoyable and comfortable for participants as the real-world evaluation. A comparison of the (H)EV sounds evaluation in the real-world and using the proposed methodology reveals that the proposed methodology is quicker compared to the real-world environment (8 minutes per participant compared to 40 minutes per participant, and 1 week compared to 1 month for 14 participants). This is because of difficulties in the real-world experimental set up such as vehicle operational failures, weather and traffic problems. Furthermore, methodology-v3 uses non-interactive way of evaluating (H)EV sounds which is more convenient and quicker than its interactive counterpart. This research shows that interactive way of evaluating (H)EV sounds is lengthier requiring 4.17 minutes per experimental condition in study 1 (25 minutes for 6 conditions). On the other hand, the non-interactive version of the proposed methodology requires only 0.81 minutes per experiment condition (25 minutes for 31 conditions) in study 2 and 1.14 minutes per experimental condition (8 minutes for 7 conditions) in study 3.

External validity is an important and debatable issue of any laboratory experiment [76]. Any experimental methodology is only effective if its results accurately predicts or reasonably generalises the real world. This is also a long debated, yet an unanswered question in the literature on VEs [109]. Study 3 showed that the methodology accurately predicts pedestrians' real world evaluations of detectability of EV sounds and their real-world impression of the powerfulness and pleasantness of the vehicle brand. It also generalises how recognisable pedestrians find these sounds in the real world. It is usually difficult to prove external validity and currently no existing automotive sound quality evaluations have been externally validated. Therefore, the ecologically and externally validated methodology developed in this thesis is an important and novel contribution in the area of automotive sound quality evaluation.

Overall, the methodology combines the benefit of the laboratory listening methods by being quick, convenient, reliable and allowing good experimental control, and real-world evaluations by being ecologically and externally valid.

7.2.2. Limitations

The methodology uses a novel software tool, ESS, for simulating VEs. The methodology mainly suffers from few technological limitations of the simulator software and the hardware used. In this research, a gamepad was used by participants for navigating the VE in the interactive version of the methodology. Participants found the controls of the gamepad difficult to learn and use. Therefore, they could not navigate the VE properly or evaluate the target EV while navigating. Moreover, they found using a gamepad for navigation unnatural because of the inability to turn pedestrian’s head while stationary specially to see vehicles on their sides before crossing any junction. Nevertheless, changes in the gamepad controls to make it easy to learn and use or use of a different and easier navigation device might make the interactive way of evaluating more convenient and quick. In future, interactivity may become a valuable addition to automotive exterior sound quality evaluations.

Currently, the ESS interface does not have buttons that participants can press to indicate vehicle detection. The ESS interface only supports rating scales that can record time of every instant the scale is moved. Therefore, a detection scale was chosen as an alternate option to detection buttons during this research. Further software enhancement to introduce press button and slider scales simultaneously in an evaluation interface would ease the participant-interface interaction.

7.3. How should (H)EV Exterior Sounds be Evaluated?

The research makes the following recommendations for evaluating (H)EV exterior sounds. Figure 7.1 summarises these guidelines.

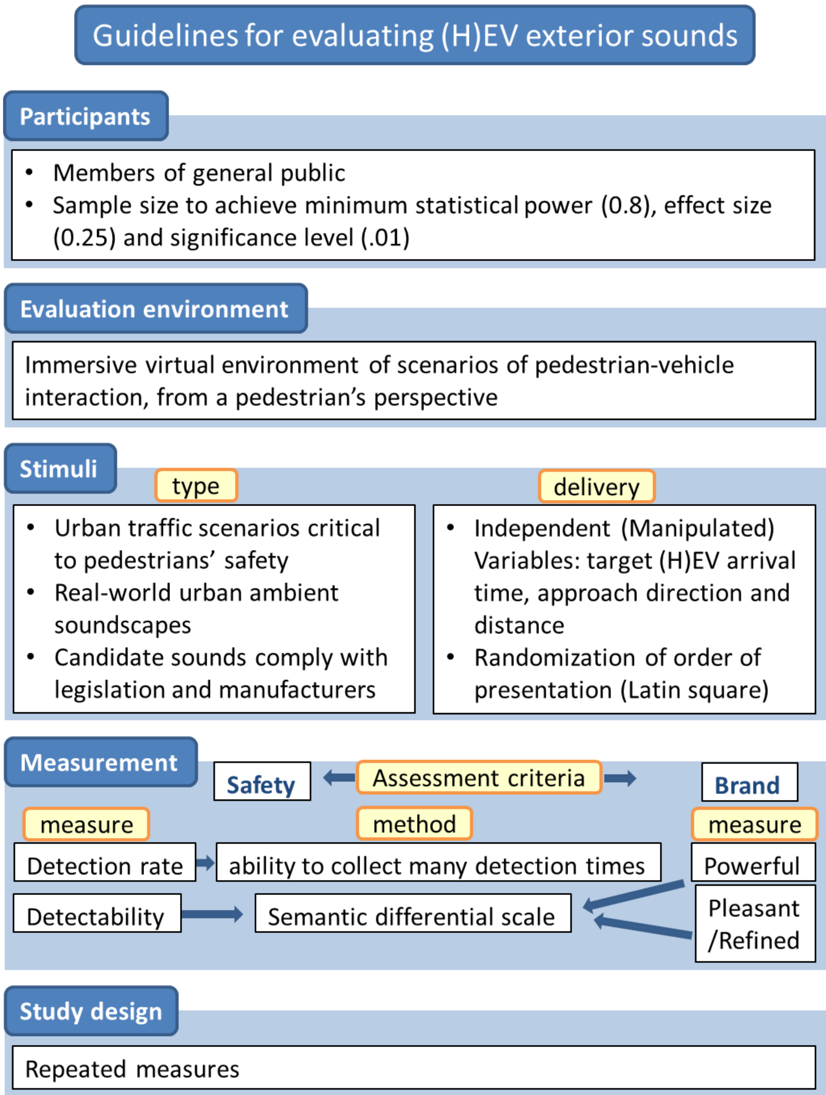


Figure 7.1 Guidelines proposed for evaluating (H)EV exterior sounds

7.3.1. Participants

Automotive interior sound quality evaluation mostly uses NVH experts and vehicle brand managers as participants for evaluating sounds [58]. However, in the context of (H)EV exterior sounds it is the evaluation of these sounds by the general public that is important. Therefore, participants should be members of the general public instead of members of the vehicle development team or a special interest group.

The sample size depends on how the data collected will be used and in particular, what analysis would be performed. Evaluations that are exploratory in nature and do not require any inferential statistics could use a small sample size (say n = 6 to 12). The minimum sample size here, should be determined by reaching theoretical saturation point, i.e., a point after which no additional insight to the inquiry can be gained [80].

For evaluations that require inferential statistics for hypothesis testing, the sample size should be such that the statistics to be used on the data achieves the standard recommended values for: minimum statistical power = 0.8 [82] and type I error probability, α= 0.05, with a medium effect size, f= 0.25 [82] as these are standard and widely used.

7.3.2. Evaluation environment

This research shows that virtual environments are a new alternative to conventional environments of laboratory listening rooms or on-road test tracks. They can combine the benefits of the laboratory listening methods by being quick, convenient and allowing good experimental control, and real-world evaluations by having a more appropriate context and being more ecologically valid. Therefore, it is recommended to evaluate (H)EV exterior sounds in immersive virtual environments of scenarios of real life pedestrian-vehicle interactions from a pedestrians' perspective.

7.3.3. Stimuli

7.3.3.1. Stimuli selection:

Research with visually impaired and orientation and mobility experts, as well as analysis of pedestrian-vehicle accidents nation-wide have identified the most common traffic scenarios for pedestrian-vehicle interactions that are critical to pedestrians' safety (see section 2.2.3) [10]. These scenarios primarily include vehicle manoeuvres at low speeds (below 48 kph) in locations such as straight roads, crossroads, T-junctions and parking lots [10], [44]. These scenarios are used in most on-road (H)EV sounds' evaluations [9], [31], [32], [35]–[37] as they provide an appropriate context. This research also recommends using these urban traffic scenarios critical to pedestrians' safety. The VE setup should be able to simulate such scenarios from a pedestrians' perspective. Additionally, the evaluations should take place in the presence of real-world urban ambient soundscapes. This further increases ecological validity of the evaluation experiment.

Future (H)EV sounds will be governed by the respective legislation. However, manufacturers will also play an important role in deciding the sounds that should reinforce their brand. Therefore, legislators and manufacturers are the key stakeholders in finalising sounds for a particular (H)EV. Thus, the candidate sounds selected for evaluation must comply with the legislation and manufacturers' requirements.

The choice of sounds is also governed by the purpose of evaluation [58]. Evaluating a set of candidate electric vehicle sounds involves comparing the sounds against one another on some evaluation criteria [10], [31], [32], [35]. The research provides evidence that the A-weighted SPL, loudness, sharpness, and roughness metrics of (H)EV exterior sounds determine the detection rate and powerfulness and pleasantness of the (H)EV based on its exterior sounds. This supports the existing research on audibility [24], [25], and automotive sound quality [26] that have found that these metrics are the key acoustic features that influence ICEV sound quality.

If the purpose of the evaluation is the initial testing of numerous sounds of wide acoustical variety so as to narrow down the choices for (H)EV sounds, then the candidate sounds must have sufficient variation in these metrics. This will ensure these sounds will elicit variation in evaluation ratings. Later when finalising the (H)EV sound, selected candidate sounds from the initial testing could be used.

7.3.3.2. Stimuli presentation:

This research shows that target vehicle's arrival time, approach direction and distance of travel from pedestrian's position is an important element in the design of the experiments for evaluating (H)EV sounds. Firstly, varying the arrival time throughout the experimental conditions reduces the expectation bias, as participants are unable to predict and expect when the target car will arrive with the VE scenario. Moreover, varying the arrival time, approach direction and distance throughout the experimental conditions just like a real world scenario increases experiment's ecological validity and helps participants to think, react and pay similar attention as a pedestrian in the real world. The research also shows that increase in the target vehicle's arrival time slows pedestrians' detection rate of the vehicle. Moreover, increase in the vehicle's distance from the pedestrian causes pedestrians to perceive the (H)EV less powerful from listening to its sounds. Therefore, the (H)EV's arrival time at the pedestrians' position, its direction of approach and its distance from the pedestrian's position should be included as independent variables in the evaluation experiment.

Additionally, the presentation order of the experimental conditions should be randomized using any standard technique such as balanced Latin square [79], or complete counterbalancing [79]. This will help eliminate the sequence effect [79].

7.3.4. Measurement

Legislation mandates that (H)EVs should emit additional sounds to alert pedestrians of the vehicles' approach to prevent potential collisions. These sounds will also influence pedestrians' impression of the vehicle brand. Current methods for evaluating (H)EV exterior sounds focus on "pedestrians' safety" but overlook the influence these sounds will have on the "vehicle brand". Therefore, this research recommends that the (H)EV exterior sounds need to be assessed not only to ensure pedestrians' safety but also to ensure they reinforce the vehicle brand.

Pedestrians' safety could be assessed using the target vehicle's "detection rate", the rate at which it is detected by the pedestrians. Detection distance [9], [31]–[33], [35], [49] and time-to-vehicle arrival [10], [48] are the measures most commonly used by researchers to evaluate the detection rate. This research recommends that the measurement method of the vehicle's detection rate should be able to collect many instances of detection. Additionally, the research also proposes that pedestrians should rate the "detectability" of (H)EV sounds on a bipolar semantic scale.

Study 2 found that using real-world ambient soundscape in an evaluation experiment resulted in 68% participants making 'detection error' by confusing the target vehicle with the spikes in the ambient soundscape. In real-world, pedestrians have to identify and detect the vehicle in the presence of other non-vehicle based ambient sounds. Thus, real-world vehicle detection is a more constant and subjective process [10]. The same could be achieved in a listening experiment by using a detection-time-measurement-method that has the following characteristics:

I. An option to record many instances of detections to accommodate for and monitor the participants self-reported detection errors if and whenever they mistake a vehicle for transient ambient sound(s).

II. A scale to subjectively evaluate ‘detectability’ of the vehicle sounds.

Study 2 indicated that these options would make the detection task more representative of the real-world and give participants more confidence in their results.

Pedestrians’ impression about the vehicle brand could be assessed using the standard dimensions of automotive sound quality that are already in existence for conventional vehicles. Study 2 found that the semantic “pleasant” that is traditionally used for ICEV sounds may be inappropriate for (H)EV sounds, but study 3 did not find any such results. Therefore, when evaluating more representative or ICEV-like sounds impression of the vehicle brand could be evaluated in the standard dimensions of “weak − powerful” and “unpleasant − pleasant” measured on semantic differential scales [26], [28]. However, when evaluating non-vehicle-like or unrecognisable simulated sounds, other standard semantics from the field of automotive sound quality such as “powerful” and “refined” could be used [26].

7.3.5. Study design

A repeated measures study design should be preferred as it more convenient for auditory evaluations (see section 3.2.3). This design eliminates the need to have equivalent groups and reduces the sample size compared to an independent group design.

7.4. Implications of the Findings to the Existing Knowledge

7.4.1. What do the findings mean for automotive sound quality?

Currently, policy makers place emphasis on ensuring that the exterior (H)EV sounds are detectable and intuitively recognizable as a vehicle so that can effectively alert pedestrians and other road users of the vehicles' approach to ensure their safety. However, vehicle companies are concerned about how (H)EV sounds would also influence pedestrians' impressions of the vehicle brand. Pedestrians hearing (H)EV exterior sounds could evaluate the (H)EV as a brand, in terms of simply liking to hear the EV pass-by, or as a potential consumer who may want to purchase the vehicle. Thus, they would play an important role in reinforcing the brand image of the vehicle.

Traditionally, automotive sound quality is measured and described using well-established dimensions of emotional evaluations that can effectively discriminate and distinguish the different types of car sounds [26], [28], [57], such as, sounds of different characters like − 'luxury', 'sporty'; and sounds from different manufacturers [26], [28], [57]. Most sound quality researchers use two underlying dimensions of emotional evaluation - where one dimension describes the strength or the power aspect of the vehicle and the other describes the aspects related to comfort and pleasantness of the vehicle [26]. These measures are used for the sounds of ICEVs. This research showed that similar measures can also be used to describe the impressions of the vehicle brand from listening to the (H)EV exterior sounds.

Therefore, it is suggested that the (H)EV exterior sound quality should be evaluated in terms of the following measures:

I. Detection rate of sounds
   - expressed in terms of detection distance or time-to-vehicle arrival

II. "Detectability" of sounds
   - expressed as ratings on semantic scales

III. "Recognisability of the sounds" as a vehicle
   - expressed as ratings on semantic scales

IV. Emotional characteristics of the sound
   - expressed in terms of standard dimensions of vehicle sound quality

Here, the first three measures are to ensure the (H)EV exterior sounds are effective in alerting the pedestrians of the vehicle approach, whereas the last measure is used to understand how these sounds influence perception of the vehicle brand. Among these measures, detection rate should take precedence as pedestrians' safety is currently the most pressing issue for (H)EV sounds. This is followed by measuring emotional characteristics in standard dimensions of vehicle sound quality. This is because in the long run manufacturers are keen to distinguish themselves in the vehicle market. Although, measuring detectability and recognisability of (H)EV exterior sounds are not as important as other measures, they complement the detection rate measure for a more comprehensive evaluation of the (H)EV sounds for pedestrians' safety.

Study 2 and study 3 show that these measures are not mutually exclusive. Particularly, detection rate of (H)EV exterior sounds does not correlate with the existing perceptual dimensions of automotive sound quality. Therefore, the vehicle sounds that are more detectable may not be more recognizable, or portray a positive impression of the vehicle brand. Overall, in context of (H) EV, exterior sounds pedestrians' safety is the primary requirement, but how these sounds influence the impression of the vehicle brand cannot be overlooked. A more holistic evaluation of the (H)EV exterior sound quality should assess these sounds in terms of all these contrasting measures.

In study 2, the sound quality measures namely, detection rate, powerfulness and pleasantness have significant strong correlation ($p<.05$) with metrics of SPL, loudness, roughness and sharpness of the (H)EV exterior sounds (see Table 5.5 and Table 6.5). Previous research shows that the same metrics are key in determining and influencing perception of automotive interior sound quality [26]. The results from study 2 indicate that, just like the vehicle interior sounds, these metrics influence (H)EV exterior sound quality. In particular, the (H)EV sounds' detection rate had a positive linear relation with the SPL dB(A), which means as the SPL dB(A) increased the target car sounds were detected faster. Similar results have been found in other detection tests of vehicle sounds [9], [10]. This fact is also supported by the fundamental auditory signal detection theories that states SPL in dB(A) as a major determinant of the audibility of sounds [11]. However, one sound did not follow this relationship (see section 5.4.6) and was detected much faster than some sounds with similar or higher decibel levels. In this research detection rate was not correlated to other key metrics (loudness, roughness and sharpness). Therefore (H)EV sounds' detectability may be affected by other metrics not commonly used in automotive sound quality research.

Additionally, the research provides more evidence that for sounds with wide acoustic variety in metrics, A-weighted SPL predicts the rate at which pedestrians detect a vehicle. However, sounds with low acoustic variety (within 2 dB difference) may have significantly different detection rate and recognisability. Study 3 however used only three sounds that had very narrow variation in these metrics. Therefore, no significant correlation was found in study 3.

7.4.2. What do the findings mean for auditory detection and evaluation?

Study 2 and 3 both show that rate of detecting the (H)EV sounds is dependent on arrival time of the target vehicle. Previous research in the field of auditory signal detection indicates that an uncertainty in the onset of a target signal in the presence of background noise leads to decrease in detectability [108]. An increase in the time of the onset of target signal within an experimental condition slows down or reduces the listener's ability to detect the signal [108]. A reason proposed for this is that as uncertainty of the signal presence or onset time increases, the listeners become more fatigued resulting in the decrease in their performance in detection [108].

This research found that increase in the target vehicle's arrival time within an experimental condition slows down a participants' rate of detecting a target vehicle sound, i.e. it reduces participants' ability to detect a target vehicle sound. This phenomenon is in agreement with the above observations in auditory signal detection [108]. Therefore, arguably an increase in the target vehicle's arrival time, decreases the listener's level of attention and increases the fatigue. This reduces their rate of detecting the vehicle.

Previous research suggests that the increase in the background sound, decreases the detection rate [108]. An increase in the randomness of the background sound can decrease the listener's capability to detect the target sound [108]. This also applies to detecting vehicle sounds in presence of real-life ambient soundscape.

Study 2 provides evidence that participants make more detection errors due to fluctuations in the background sound. Similar detection errors have been found in previous studies involving vehicle detection in urban soundscape [31], [38], [48]. This research indicates that in the presence of real-life ambient soundscape participants' find the vehicle detection difficult. In real world, pedestrians have to identify and detect the vehicle in the presence of other non-vehicle based ambient sounds. As such, pedestrians tend to detect and identify the vehicles more continuously and subjectively [10]. Study 2 indicates that if a listening experiment involves detecting vehicle sounds in presence of real-life ambient soundscape then the detection task will become more representative of the real-world vehicle detection through a detection-time-measurement-method with following characteristics:

I. An option to record many instances of detections to accommodate for and monitor the participants' **self-reported detection errors** if and whenever they mistake a vehicle for the transient sounds in the ambience.

II. A scale to subjectively evaluate 'detectability' of the vehicle sounds.

7.5. Research Impact and Knowledge Contribution

Firstly, this research has produced guidelines for evaluating (H)EV exterior sounds on the criteria of pedestrians' safety and vehicle brand. The guidelines are more general so that they can be applied to any automotive exterior sound quality evaluation. Since VE is an essential part of the proposed methodology, therefore the guidelines can also be applied to other areas that use VE simulation such as flight simulators and vehicle interior NVH simulators. Additionally, these guidelines and the overall knowledge gained in this research may be used towards enhancement of sound quality approaches in non-automotive backgrounds such as aircraft noise and machinery noise. This research positively tested the hypothesis that “detection rate is affected by target vehicle’s arrival time”, and “pedestrians have tendency to make detection errors in the presence of a real world ambient soundscape”. This new knowledge may be used towards achieving more ecologically valid listening experiments and understanding the cognitive processes of a pedestrian/listener evaluating vehicle sounds.

The proposed evaluation methodology (in the form of the final guidelines, see section 7.3) has been proven to benefit over existing automotive sound quality approaches as follows:

I. It achieves an appropriate context (usually not found in a typical ‘laboratory listening’).

II. It provides full experimental control (not achievable in a typical on-road evaluation)

III. It has improved ecological validity (usually not found in any existing evaluation method).

IV. It has sufficient external validity (currently no existing evaluation methods have proved their external validity).

The final methodological guidelines (see section 7.3) can be directly applied to the automotive industry in their NVH process of vehicle design. It can be used by transportation researchers, automotive engineers, manufacturers and legislators to understand how pedestrians will evaluate the new (H)EV sounds. Overall, it is hoped that the application of this research would ultimately benefit the public, especially pedestrians.

7.6. Recommendations for Future Work

I. A further investigation is required to see how the individual psychoacoustic metrics (SPL (dB(A)), loudness, roughness and sharpness) influence the individual (H)EV exterior sound quality measures (“detection rate” and emotional evaluation of “recognizability”, “detectability”, “powerfulness” and “pleasantness”). A detailed psychoacoustic analysis may reveal the acoustic features responsible for increasing the detectability of (H)EV sounds while keeping SPL constant. This would give an opportunity to create ‘smart’ (H)EV sounds that have higher detectability at lower SPL than combustion engine vehicles. Such analysis is beyond the scope of this thesis.

II. Research suggests that background sound can affect pedestrians’ detection rate [10], [31]. In future, the effect of ambient soundscape on pedestrians’ evaluation of vehicle sounds can be examined using the proposed methodology.

III. Currently, there is no research on how mass usage of (H)EVs emitting new sounds may affect the urban soundscape in terms of acoustic metrics and subjective appraisal. Research should be conducted to evaluate multiple (H)EVs emitting same or different exterior sounds.

IV. This research used convenience sampling of students and staff members at the University of Warwick. However, this sample is not fully representative of adult pedestrians in the UK. Inclusion of non-University staff and people without a Science and Engineering background will provide a more homogenous sample of adult pedestrians. Future work can be conducted on evaluating (H)EV sounds using the final methodological guidelines and include participants from all age group. In particular, it would be interesting to conduct studies on children, visually impaired and older population (more than 70 years of age).

V. Future studies could extend, apply and test the final evaluation guidelines in the area of non-automotive product sound quality. This would help in further enhancement of the methodology to suit the respective field of application.

VI. Future studies could extend, apply and test the final evaluation guidelines in other areas of VE simulation. This would help in further enhancement of the methodology to suit the respective field of application.

Chapter 8: Conclusions

8.1. Conclusions

This research addressed the question: ***"How should (H)EV exterior sounds be evaluated?"*** This question was answered through the development of methodological guidelines for evaluating (H)EV exterior sounds. The testing and validation of the methodology shows that it is an improvement over the existing methods for automotive exterior sound evaluation.

8.1.1. Learning about the criteria of evaluating (H)EV sounds

It was found that (H)EV sounds must satisfy the following criteria from the perspective of legislation, manufacturers, noise control authorities and the public:

I. Ensuring pedestrians' safety: The legislation requires (H)EV sounds to be quickly detectable by pedestrians so that they can avoid a potential collision.

II. Reinforcing the brand image, as desired by the manufacturer.

III. Ensuring soundscape benefits: The noise control authorities and the public want (H)EV sounds to help in traffic noise reduction.

This research aimed at understanding and improving methods for evaluating (H)EV exterior sound quality for its use by the automotive industry, sound quality experts, transportation researchers and policy makers. Therefore, the research focused only on the criteria of safety and brand. Thus, a ***methodology-v1 was***

proposed to holistically evaluate (H)EV exterior sounds on the criteria of pedestrians' safety and brand reinforcement, through an experimental approach that assesses 'detectability' of these sounds and emotional evaluation of the vehicle based on listening to its sounds respectively. Reviewing the state-of-the-art automotive sound quality methods suggested that the evaluation environment should provide a better context through presence of realistic visual and auditory stimuli of pedestrian-vehicle interactions. Thus, ***methodology-v1 proposed using immersive VEs within listening rooms*** to simulate realistic traffic scenario(s) of pedestrian-vehicle interaction(s) critical to pedestrians' safety (e.g. (H)EV moving at low speeds in parking lots, T-junctions, and crossroads), from a pedestrian's perspective.

8.1.2. Understanding and improving methods for evaluating (H)EV exterior sounds

An iterative process tested methodology-v1 through evaluation experiments to improve it based on the experimental results, participants' feedback and theory. An Exterior Sound Simulator (ESS) is a novel software tool that synthesizes the visuals, sounds and an ambient soundscape of an EV moving in a town, from a pedestrian's perspective. ESS was installed in a closed semi-anechoic room, and this set-up was used as the laboratory for all the evaluation experiments.

An important feature of simulating VEs is that the simulation tool can offer more interactivity by allowing participants to freely navigate the virtual town and interact with the target vehicle just like a real-world pedestrian. This feature was explored using study 1. It was learned that increasing the level of interactivity makes experiments more ecologically valid and more enjoyable but reduces repeatability across participants and quadruples the experiment duration. Thus, studies 2 and 3 used a non-interactive way of evaluating (H)EV sounds where participants were exposed to pre-determined scenarios of interacting with the target (H)EV.

Study 2 tested methodology-v1. To account for variability in the direction traffic can approach a pedestrian in the real world, the experiment was improved by altering the target EV's arrival time and direction and distance of approach throughout the experimental conditions, just as in the real world. This enhanced the ecological validity of the methodology. This also avoids order effects that may be apparent with existing evaluation procedures. Moreover, it helped avoid any "expectation bias" in vehicle detection due to a participant starting to expect a target vehicle's arrival at a fixed time or upon receiving some visual cues. Thus, this further enhances the validity of the methodology that was in development.

Results showed that the target vehicle's arrival time and its direction, and thus distance from the pedestrian's position, significantly affected participants' rate of detecting the vehicle and emotional evaluations of the vehicle exterior sounds. Variation and randomization of these factors are required to reduce 'expectation bias' and achieve more ecologically valid scenarios. Hence, despite their neglect in existing automotive sounds' detection and evaluation methods, the target vehicle's arrival time, direction and distance of approach are important elements of experimental design.

Additionally, an ambient soundscape of a real-world urban environment was used as a background in every experimental condition to make evaluations more realistic. However, this resulted in 68% participants detecting a vehicle more than once and self-reporting that they made 'detection error(s)' by confusing the target vehicle with the spikes or transients in the ambient soundscape. In the real-world, pedestrians have to identify and detect the vehicle in the presence of other non-vehicle based ambient sounds. Thus, real-world vehicle detection is a continuous and subjective process [10]. It was concluded that to achieve a similar real-world detection process within a listening experiment a detection-time-measurement-method should have the following characteristics:

I. An option to record many instances of detections to accommodate for and monitor the participants **self-reported detection errors** if and whenever they mistake a vehicle for transient ambient sound(s).

II. A scale to subjectively evaluate 'detectability' of the vehicle sounds.

These options make the detection task more representative of the real-world, thus making the experiment more ecologically valid. Furthermore, the 'recognisability' of the candidate sounds as emanating from a vehicle was identified as an important parameter for evaluation. Consequently, methodology-v1 was enhanced to methodology-v2 that included subjective assessment of the candidate sounds' "detectability" and "recognisability as a vehicle".

Study 3 tested the external validity of the methodology-v2 by comparing results of two listening evaluation experiments: a real-world experiment and a replicated virtual-environment experiment. Both experiments used the same methods, stimuli and participants, differing only in evaluation environment. Results showed that pedestrians' subjective evaluations of detectability and emotional characteristics of (H)EV exterior sounds within the ESS' VE can be generalized to a similar real-world setting. Similarly, the pedestrians' ranked order of the (H)EV sounds' recognisability and (H)EV's detection distance within the ESS' VE can be generalized to a similar real-world setting.

External validity of the VEs has always been an important issue in the literature. However, no existing automotive detection and sound quality evaluation methods have been ecologically or externally validated. Therefore, ***the ecologically and externally validated methodology developed in this thesis is an important and novel contribution in the area of automotive sound quality evaluation***.

In study 3, participants detected target sounds only when the sounds became audible as well as recognizable as a vehicle. This suggests that in the real-world traffic scenarios that comprise both vehicular and non-vehicular sounds, a pedestrian detecting a vehicle's sound is equivalent to hearing and then recognizing the sound as a vehicle. Thus, final methodology-v3 combined 'recognisability', 'detection' as a single measure. To achieve this, participants could be informed of the presence of vehicular and non-vehicular ambient sounds and asked to detect a 'vehicle'.

8.1.3. Overall learning

This research has demonstrated that VEs by using real life traffic scenarios and ambient soundscapes provide a more appropriate context, external reliability and greater experimental control than in existing automotive sounds' evaluation methods. A control on almost every aspect of experimental design, such as ambient sounds, visuals, traffic, and target vehicle's manoeuvre and sound, enables investigating their effects on pedestrians' response. This provides an opportunity for a greater understanding of how pedestrians evaluate vehicle sounds. This research therefore, is an important step towards the development of a more holistic method of evaluating vehicle exterior sounds. The proposed methodology for evaluating (H)EV exterior sounds has been shown to be an enhancement over the existing automotive sound quality methods through greater experimental control, more realistic context, and ecological and external validity. The final methodological guidelines are recommended for use by the automotive industry to enhance their NVH process.

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Appendix 1: Participant Recruitment Material

1.1. Invitation Letter

Dear Sir/Madam,

I am writing to invite you to participate in a doctoral research project carried out by Sneha Singh based at the University of Warwick. The project is named “developing appropriate methods for evaluating electric vehicles’ exterior sounds”. It aims to develop and use appropriate methods for conducting sound quality evaluations of exterior electric vehicle sounds using a simulator that creates a virtual environment of a traffic area in a typical UK town. It also aims to develop appropriate methods for performing evaluations on-road in real life environments. Additionally, it aims to use the simulator to understand the influence of ambient soundscapes on evaluations of vehicles by the pedestrians.

I would like to invite you to participate in a listening evaluation of exterior sounds of electric vehicles that should last between 20 to 40 minutes.

All information collected about you during the course of the study will be kept strictly confidential, and any information about you that leaves WMG will have your name and contact details removed so that you cannot be recognised. If you decide to take part you are entitled to withdraw at any time without reason.

Please find attached the information sheet which provides more details. If you agree to participate then please choose a convenient time and bring the signed consent form (attached with this email) when you come for evaluation. If you would like to take part or require any further information please contact me on the details provided.

Yours faithfully,
Sneha Singh
PhD Student
WMG
University of Warwick
Email: singh_s@wmg.warwick.ac.uk
Work phone: 024 761 51579
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1.2. Poster

Developing appropriate methods for evaluating electric vehicles' exterior sounds

We would like to invite you to participate in a listening evaluation of exterior sounds of electric vehicles.

These evaluations are part of a PhD research project that uses an Exterior Sound Simulator to create a virtual town containing an electric vehicle carrying out different manoeuvres.

Evaluations will be held at the 'Soundroom' laboratory at the International Digital Laboratory at the University of Warwick. You will be seated in the Soundroom and exposed to visuals and sounds of traffic locations like car parks, road crossings, and roundabouts of a virtual town. You will be asked to navigate the virtual town using a joystick and/or rate the sounds of a vehicle using an iPad interface. Similar evaluations will also be conducted on-road where you will stand on a pavement as a pedestrian and evaluate the sounds of an electric car that will pass-by at regular intervals.

Virtual town

Soundroom evaluations

On-road evaluations

Contact:
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"Research approved by Biomedical and Scientific Research Ethics Committee"

1.3. Participant Information Sheet for Study 1

Study Title: Developing appropriate methods for evaluating electric vehicles' exterior sounds

Invitation

We would like to invite you to participate in our research study. Before you decide if you would like to participate, we would like you to understand what the research is about, and what it would involve for you. This should take about 10 minutes to read. If there is anything unclear or you need more information feel free to contact us:

Name: Sneha Singh
Email: singh_s@wmg.warwick.ac.uk
Mobile: 07753385802

What is the study about?

This study is part of a doctoral research project that uses an Exterior Sound Simulator (ESS). ESS is a new technology that simulates a virtual town and synthesizes visual and audio stimuli of an electric vehicle moving in the virtual town and carrying out different manoeuvres, as seen and heard by an observer external to the vehicle. In this study, a virtual environment will be created using this simulator inside the Soundroom laboratory located in the International Digital Laboratory at WMG. Since ESS is new to the area of automotive exterior sound quality evaluations, this study will focus on understanding the experiences of participants within this environment, identifying potential feasibility issues of using this simulator and validating it as a practical engineering tool. The feedback gained from this study will be used in planning future listening experiments using this technology.

Why have I been invited?

The study requires gaining feedback on the simulator and the virtual environment created by the simulator from anyone that can be representative of an adult pedestrian or an external observer to the vehicle. Therefore, anyone above 18 years of age who is not pregnant and has no hearing and uncorrected visual impairment meets our selection criteria. We are recruiting people from the general public, primarily within the University of Warwick and their referrals.

Do I have to take part?

Taking part is voluntary. Please read the information sheet about what it involves. If you agree to take part, we will ask you to sign a consent form, but you may withdraw anytime.

What will I have to do if I take part?

This study will be held in the Soundroom laboratory. After a short briefing you will be exposed to a traffic location in a virtual town. The volume range of all the sounds you will hear lies within 30 – 80 dB range. Additionally, the visuals you will see are representative of a typical UK town and are free from any content that may cause you to have any sudden jumps or shocks. You will be asked to navigate the virtual town using a gamepad. The path you take will be saved by ESS software. You will be asked to answer a questionnaire at the beginning containing a few questions related to your demographics; concentration levels; past experiences of any virtual environments, visual media and listening evaluations; past experiences of motion sickness; and your current state of fitness. Only if you self-report as fit, you are allowed to proceed with the evaluation.

At the end you will be asked to answer another questionnaire relating to your experience and feedback on the various aspects of this study. By returning the questionnaire, you are giving consent for the information that you have provided to be included in this study. The entire process should last no longer than 40 minutes.

What are the advantages and disadvantages of taking part?

The advantages are that you will be involved in research that will contribute towards the development of a new methodology for automotive sound quality evaluations.

The disadvantage is the time commitment of 40 minutes for the study. Occasionally, a prolonged exposure to the virtual environment may induce some temporary motion sickness like symptoms. If you feel so, you may withdraw at any point during the study.

Has this study been approved?

An independent group of people called Research Ethics Committee looks at all research involving human participants. This study has been reviewed and approved by the Biomedical and Scientific Research Ethics Committee at the University of Warwick.

Expenses and Payments

Unfortunately, participation of this study is non-remunerated and expenses cannot be covered.

Who do I contact?

If you would like any more information please contact:

Principle Researcher	Academic Supervisors	
Sneha Singh	Professor Paul Jennings	Dr Sarah Payne
IIPSI WMG University of Warwick Coventry CV4 7AL	International Digital Laboratory University of Warwick Coventry CV4 7AL	IIPSI WMG University of Warwick Coventry CV4 7AL
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Tel: +44 (0)24 761 51579	Tel: +44(0)24 765 23646	Tel: +44 (0)24 761 51339
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If you have a complaint about any aspect related to your participation in this research please contact the following person who is a senior University official entirely independent of the study:

Deputy Registrar
Deputy Registrar's Office
University of Warwick
Coventry CV4 8UW
Email: deputyregistrar@warwick.ac.uk
Tel: 0 24 7652 3713

Will my personal information be kept confidential?

Your contact details that were collected to send you this invitation letter, information sheet, and consent form and book your time slots for an evaluation study, will be kept by Sneha Singh. Your contact details will be destroyed once the evaluation study is over or if you withdraw from it.

All information which is collected from/about you during the course of the study will be kept strictly confidential, and any information which leaves WMG will never bear your name or contact details so that you cannot be recognised. The results of the study will be anonymised. For this, you will be given an identification number to distinguish your results from others. Thus, you cannot be traced back from the data collected or the results published from the study.

During the study, all data will be stored and managed in accordance with the University of Warwick Research Data Management Policy. The questionnaires used for data collection will be kept safely in a locked cabinet and will be accessed only by the principal researcher of this study, Sneha Singh. To preserve anonymity all data will be entered and saved in a coded form into a password-protected computer, accessible only to the researcher. After this, the raw data from the questionnaires will be destroyed. The coded data will also be secured through regular back-up on secure University servers and will be kept for 10 years from the study after which it will be destroyed. It will not be possible to identify you from any published material arising from this study.

What will happen if I don't continue with the study after giving my consent?

Nothing. You are free to withdraw at any point during the study even after signing the consent form. If you decide to withdraw you may be asked your reasons and requested to complete a short feedback form. The feedback is an integral part of the study and will be used to design future studies. But again, feedback is optional and you are free to leave the experiment site whenever you want.

What will happen to the results of the study?

All results and knowledge stemmed from this study can be used for publications. I will be happy to provide you a summary report, if you ask for it any time after the study completion. In that case, your contact details will be kept till the report is sent to you, after which your contact details will be destroyed.

1.4. Participant Information Sheet for Study 2

Project Title: Developing appropriate methods for evaluating electric vehicles' exterior sounds

Invitation

We would like to invite you to participate in our research study. Before you decide if you would like to participate, we would like you to understand what the research is about, and what it would involve for you. This should take about 10 minutes to read. If there is anything unclear or you need more information feel free to contact us:

Name: Sneha Singh
Email: singh_s@wmg.warwick.ac.uk
Mobile: 07753385802

What is the study about?

This study is part of a doctoral research project that uses an Exterior Sound Simulator (ESS) to conduct listening experiments in the controlled environment of the Soundroom laboratory located in the International Digital Laboratory. ESS is a new technology that simulates a virtual town and synthesizes visual and audio stimuli of an electric vehicle performing different manoeuvres in the virtual town, as experienced by a pedestrian. Since ESS is a new tool for automotive exterior sound quality evaluations, some evaluations will be conducted to establish guidelines for its use followed by some case studies to understand the influence of ambient soundscapes on evaluations of vehicles by the pedestrians.

Why have I been invited?

The study requires evaluation of the vehicle sounds by anyone that can be representative of an adult pedestrian or an external observer to the vehicle. Therefore, anyone above 18 years of age who is not pregnant and has no hearing and uncorrected visual impairment meets our selection criteria. We are recruiting people from the general public, primarily within the University of Warwick and their referrals.

Do I have to take part?

Taking part is voluntary. Please read the information sheet about what it involves. If you agree to take part, we will ask you to sign a consent form, but you may withdraw anytime. If you feel dizzy, nauseated or sick on the day of the experiment, please contact me beforehand and we can arrange the study for another time.

What will I have to do if I take part?

The study involves a listening evaluation in the presence of a visual stimulus. This will be held in the Soundroom laboratory. After a short briefing you will be exposed to a traffic location in a virtual town. The evaluation will be no longer than 40 minutes. You will experience travelling a predefined path and interacting with 1 or more vehicle. The volume range of all the sounds you will hear lies within 30 – 80 dB range. Additionally, the visuals you will see are representative of a typical UK town and are free from any content that may cause any sudden jumps or shocks to you. Moreover, a pre-assessment has been carried out to ensure it is safe for a person to participate.

You will have to respond as soon as you hear a vehicle, and rate the vehicle based on its sounds on attributes such as being ‘powerful’, ‘refined’ ‘pleasant', ‘detectable', ‘futuristic’, ‘appropriate’, 'recognisable as vehicle'. You will be asked to answer a questionnaire at the beginning containing questions related to your demographics, previous experience of any listening evaluations or virtual environment, and if you feel well before the start of evaluation. If you self-report as ‘unwell’, for example: feeling dizzy, nauseated or sick, you will not be allowed to proceed with the evaluation. At the end you will be requested to provide an open-ended feedback on your experience and suggestions on the various aspects of the evaluation. By returning the questionnaire, you are giving consent for the information that you have provided to be included in this study.

What are the advantages and disadvantages of taking part?

The advantages are that you will be involved in research that will contribute towards the development of a new methodology for automotive sound quality evaluations.

The disadvantage is the time commitment of 20 – 40 minutes for the study. Occasionally, a prolonged exposure to the virtual environment may induce some temporary motion sickness like symptoms. If you feel so, you may withdraw at any point during the study.

Has this study been approved?

An independent group of people called Research Ethics Committee, looks at all research involving human participants. This study has been reviewed and approved by the Biomedical and Scientific Research Ethics Committee at the University of Warwick.

Expenses and Payments

Unfortunately, participation of this study is non-remunerated. Moreover, travel costs, if any, to the study will not be reimbursed, thus you should consider your travel costs beforehand.

Who do I contact?

If you would like any more information please contact:

Principle Researcher	Academic Supervisors	
Sneha Singh	Professor Paul Jennings	Dr Sarah Payne
IIPSI WMG University of Warwick Coventry CV4 7AL	International Digital Laboratory University of Warwick Coventry CV4 7AL	IIPSI WMG University of Warwick Coventry CV4 7AL
Email: singh_s@wmg.warwick.ac.uk	Email: Paul.Jennings@warwick.ac.uk	Email: S.R.Payne@warwick.ac.uk
Tel: +44 (0)24 761 51579	Tel: +44(0)24 765 23646	Tel: +44 (0)24 761 51339
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During the study, all data will be stored and managed in accordance with the University of Warwick Research Data Management Policy. The questionnaires and ipad interface used for data collection will be kept safely in a locked cabinet and will be accessed only by the principal researcher of this study, Sneha Singh. To preserve anonymity all data will be entered and saved in a coded form into a password-protected computer, accessible only to the researcher. After this, the raw data from the questionnaires and ipad will be destroyed. The coded data will also be secured through regular back-up on secure University servers and will be kept for 10 years from the study after which it will be destroyed. It will not be possible to identify you from any published material arising from this study.

What will happen if I don't continue with the study after giving my consent?

Nothing. You are free to withdraw at any point during the study even after signing the consent form. If you decide to withdraw you may be asked your reasons for the same and requested to complete a short feedback form. The feedback is an integral part of the study and will be used to design future studies. But again, feedback is optional and you are free to leave the experiment site whenever you want.

What will happen to the results of the study?

All results and knowledge stemmed from this study can be used for publications. I will be happy to provide you a summary report, if you ask for it any time after the study completion. In that case, your contact details will be kept till the report is sent to you, after which your contact details will be destroyed.

1.5. Participant Information Sheet for Study 3

Project Title: Developing appropriate methods for evaluating electric vehicles' exterior sounds

Invitation

We would like to invite you to participate in our research study. Before you decide if you would like to participate, we would like you to understand what the research is about, and what it would involve for you. This should take about 10 minutes to read. If there is anything unclear or you need more information feel free to contact us:
Name: Sneha Singh
Email: singh_s@wmg.warwick.ac.uk
Mobile: 07753385802

What is the study about?

This study is part of a doctoral research project that uses an Exterior Sound Simulator (ESS) to conduct listening experiments in the controlled environment of the Soundroom laboratory located in the International Digital Laboratory. ESS is a new technology that simulates a virtual town and synthesizes visual and audio stimuli of an electric vehicle performing different manoeuvres in the virtual town, as experienced by a pedestrian. Since ESS is a new tool for automotive exterior sound quality evaluations, some evaluations will be conducted to establish guidelines for its use followed by some case studies to understand the influence of ambient soundscapes on evaluations of vehicles by the pedestrians.

Why have I been invited?

The study requires evaluation of the vehicle sounds by anyone that can be representative of an adult pedestrian or an external observer to the vehicle. Therefore, anyone above 18 years of age who is not pregnant and has no hearing and uncorrected visual impairment meets our selection criteria. We are recruiting people from the general public, primarily within the University of Warwick and their referrals.

Do I have to take part?

Taking part is voluntary. Please read the information sheet about what it involves. If you agree to take part, we will ask you to sign a consent form, but you may withdraw anytime. If you feel dizzy, nauseated or sick on the day of the experiment, please contact me beforehand and we can arrange the study for another time.

What will I have to do if I take part?

The study involves a listening evaluation in the presence of a visual stimulus. The study will be conducted in two sessions – on-road and inside Soundroom with at least 1 month gap between the sessions. Evaluations will not exceed 40 minutes per session. The volume range of all the sounds you will hear lies within 30 – 80 dB range. Additionally, the visuals you will see are representative of a typical UK town and are free from any content that may cause any sudden jumps or shocks to you. Moreover, a pre-assessment has been carried out to ensure it is safe for a person to participate.
During on-road session, you will stand on the pavement of a residential road at the Lakeside Apartments in the University campus. An electric car will pass-by at regular intervals. Each time you will be asked to detect the car using a push button and evaluate the car based on its sounds on attributes such as being ‘powerful’, ‘refined’, ‘pleasant', ‘detectable', ‘futuristic’, ‘appropriate’, 'recognisable as vehicle'. During Soundroom session, similar evaluation will be conducted where you will experience standing on a residential road pavement and an electric car will pass-by at regular intervals. You will have to detect and evaluate the car on the same semantics as the on-road session. Before the on-road session, you will be asked to answer a questionnaire containing questions related to your demographics, previous experience of any listening evaluations or virtual environment. Before every session (on-road and soundroom) you will be asked if you feel well before the start of evaluation. If you self-report as ‘unwell’, for example: feeling dizzy, nauseated or sick, you will not be allowed to proceed with the evaluation. At the end of every session, you will be requested to provide an open-ended feedback on your experience. By returning the questionnaire, you are giving consent for the information that you have provided to be included in this study.

What are the advantages and disadvantages of taking part?

The advantages are that you will be involved in research that will contribute towards the development of a new methodology for automotive sound quality evaluations.

The disadvantage is the time commitment of 20 – 40 minutes for the study. Occasionally, a prolonged exposure to the virtual environment may induce some temporary motion sickness like symptoms. If you feel so, you may withdraw at any point during the study.

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Expenses and Payments

Unfortunately, participation of this study is non-remunerated. Moreover travel costs, if any, to the study will not be reimbursed, thus you should consider your travel costs beforehand.

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Principle Researcher	Academic Supervisors	
Sneha Singh	Professor Paul Jennings	Dr Sarah Payne
IIPSI WMG University of Warwick Coventry CV4 7AL	International Digital Laboratory University of Warwick Coventry CV4 7AL	IIPSI WMG University of Warwick Coventry CV4 7AL
Email: singh_s@wmg.warwick.ac.uk	Email: Paul.Jennings@warwick.ac.uk	Email: S.R.Payne@warwick.ac.uk
Tel: +44 (0)24 761 51579	Tel: +44(0)24 765 23646	Tel: +44 (0)24 761 51339
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What will happen if I don't continue with the study after giving my consent?

Nothing. You are free to withdraw at any point during the study even after signing the consent form. If you decide to withdraw you may be asked your reasons for the same and requested to complete a short feedback form. The feedback is an integral part of the study and will be used to design future studies. But again, feedback is optional and you are free to leave the experiment site whenever you want.

What will happen to the results of the study?

All results and knowledge stemmed from this study can be used for publications. I will be happy to provide you a summary report, if you ask for it any time after the study completion. In that case, your contact details will be kept till the report is sent to you, after which your contact details will be destroyed.

1.6. Consent Form for Studies 1 to 3

Title: Developing appropriate methods for evaluating electric vehicles' exterior sounds

Version: 4 Submission date: 30/09/2013

Consent Form

Participant Identification Number: Study Number:

Title of Project: Developing appropriate methods for evaluating electric vehicles' exterior sounds

Name of Researcher: Sneha Singh

Date: Please initial the box

1. I confirm that I have read and understand the information sheet dated..................... (Version 4) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.

3. I understand that I will be listening to traffic sounds and seeing an urban traffic location within either the Soundroom laboratory or on a residential road at the Lakeside apartments in the University of Warwick campus.

4. I understand that the results will be seen by Sneha Singh and her academic supervisors Professor Paul Jennings and Dr Sarah Payne will have access to this. I give permission for this.

5. I agree to take part in the above study.

Name of Participant: Date: Signature:

Name of Researcher: Date: Signature:

THE UNIVERSITY OF WARWICK

WMG Innovative Solutions

Appendix 2: Ethical Approval

2.1. Letter of Ethical Approval for the Research

Friday 4th October 2013

Warwick Medical School

PRIVATE
Miss Sneha Singh
c/o Dr Sarah Payne
International Institute for Product and Service Innovation
Warwick Manufacturing Group
University of Warwick
Coventry
CV4 7AL

Dear Sneha,

Study Title and BSREC Reference: *Developing appropriate methods for evaluating electric vehicles' exterior sounds – REGO-2013-534 AM01 (239-10-2012)*

Thank you for submitting your revisions to the above-named project to the University of Warwick Biomedical and Scientific Research Ethics Sub-Committee for Chair's Approval.

I am pleased to confirm that I am satisfied that you have met all of the conditions and your application meets the required standard, which means that full approval is granted and your study may commence.

I take this opportunity to wish you success with the study and to remind you any substantial amendments require approval from the committee before they can be made. Please keep a copy of the signed version of this letter with your study documentation.

Yours sincerely,

David Davies
Chair
Biomedical and Scientific
Research Ethics Sub-Committee

Biomedical and Scientific
Research Ethics Subcommittee
Enquiries: Amy Ismay
A010 Medical School Building
Warwick Medical School,
Coventry, CV4 7AL.
Tel: 02476-151875
Email: A.C.Ismay@warwick.ac.uk

THE UNIVERSITY OF
WARWICK

Appendix 3: Questionnaires for Study 1

3.1. Presence Questionnaire by Witmer and Singer (1998) [63]

Item Stems	Factors	Subscale	*ITCorr*
1. How much were you able to control events?	CF	INV/C	0.43*
2. How responsive was the environment to actions that you initiated (or performed)?	CF	INV/C	0.56*
3. How natural did your interactions with the environment seem?	CF	NATRL	0.61*
4. How completely were *all* of your senses engaged?	SF		0.39*
5. How much did the visual aspects of the environment involve you?	SF	INV/C	0.48*
6. How much did the auditory aspects of the environment involve you?	SF	AUD[a]	0.32*
7. How natural was the mechanism which controlled movement through the environment?	CF	NATRL	0.62*
8. How aware were you of events occurring in the real world around you?	DF		0.03
9. How aware were you of your display and control devices?	DF		−0.14
10. How compelling was your sense of objects moving through space?	SF	INV/C	0.51*
11. How inconsistent or disconnected was the information coming from your various senses?	RF		0.33*
12. How much did your experiences in the virtual environment seem consistent with your real-world experiences?	RF, CF	NATRL	0.62*
13. Were you able to anticipate what would happen next in response to the actions that you performed?	CF	INV/C	0.43*
14. How completely were you able to actively survey or search the environment using vision?	RF, CF, SF	INV/C	0.59*
15. How well could you identify sounds?	RF, SF	AUD[a]	0.34*
16. How well could you localize sounds?	RF, SF	AUD[a]	0.30*
17. How well could you actively survey or search the virtual environment using touch?	RF, SF	HAPTC[b]	0.15
18. How compelling was your sense of moving around inside the virtual environment?	SF	INV/C	0.62*
19. How closely were you able to examine objects?	SF	RESOL	0.55*
20. How well could you examine objects from multiple viewpoints?	SF	RESOL	0.49*
21. How well could you move or manipulate objects in the virtual environment?	CF	HAPTC[b]	0.11
22. To what degree did you feel confused or disoriented at the beginning of breaks or at the end of the experimental session?	RF		−0.06
23. How involved were you in the virtual environment experience?		INV/C	0.52*
24. How distracting was the control mechanism?	DF		0.37*
25. How much delay did you experience between your actions and expected outcomes?	CF	INV/C	0.41*
26. How quickly did you adjust to the virtual environment experience?	CF	INV/C	0.42*
27. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	CF	INV/C	0.45*
28. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?	DF	IFQUAL	0.44*

Item Stems	Factors	Subscale	*ITCorr*
29. How much did the control devices interfere with the performance of assigned tasks or with other activities?	DF, CF	IFQUAL	0.44*
30. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?	DF	IFQUAL	0.51*
31. Did you learn new techniques that enabled you to improve your performance?	CF		0.33*
32. Were you involved in the experimental task to the extent that you lost track of time?		INV/C	0.41*

Note. Major Factor Category: CF = Control Factors, SF = Sensory Factors, DF = Distraction Factors, RF = Realism Factors. Subscales: INV/C = Involvement/Control, NAT = Natural, AUD = Auditory, HAPTC = Haptic, RES = Resolution, IFQUAL = Interface Quality. ITCorr = Pearson correlation coefficients between PQ item scores and the PQ Total Score.

[a]No auditory stimulation was provided in our experiments.

[b]No haptic stimulation was provided in our experiments.

$*p < .001$

3.2. Simulator Sickness Questionnaire by Kennedy et al. (1993) [98]

Computation of SSQ Scores

	Weight		
SSQ Symptom[a]	***N***	***O***	***D***
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total[b]	[1]	[2]	[3]

Score
N = [1] × 9.54
O = [2] × 7.58
D = [3] × 13.92
TS[c] = [1] + [2] + [3] × 3.74

[a]Scored 0, 1, 2, 3. [b]Sum obtained by adding symptom scores. Omitted scores are zero. [c]Total Score.

3.3. Immersive Tendency Questionnaire by Witmer and Singer (1998) [63]

Item Stems	Subscale	*ITCorr*
1. Do you ever get extremely involved in projects that are assigned to you by your boss or your instructor, to the exclusion of other tasks?		0.26*
2. How easily can you switch your attention from the task in which you are currently involved to a new task?		0.26*
3. How frequently do you get emotionally involved (angry, sad, or happy) in the news stories that you read or hear?		0.27*
4. How well do you feel today?		0.20
5. Do you easily become deeply involved in movies or TV dramas?	FOCUS	0.49**
6. Do you ever become so involved in a television program or book that people have problems getting your attention?	INVOL	0.47**
7. How mentally alert do you feel at the present time?	FOCUS	0.40**
8. Do you ever become so involved in a movie that you are not aware of things happening around you?	INVOL	0.56**
9. How frequently do you find yourself closely identifying with the characters in a story line?	INVOL	0.53**
10. Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?	GAMES	0.55**
11. On average, how many books do you read for enjoyment in a month?		0.16
12. What kind of books do you read most frequently? (CIRCLE ONE ITEM ONLY!) Spy novels Fantasies Science fiction Adventure Romance novels Historical novels Westerns Mysteries Other fiction Biographies Autobiographies Other non-fiction		—
13. How physically fit do you feel today?	FOCUS	0.30**
14. How good are you at blocking out external distractions when you are involved in something?	FOCUS	0.46**
15. When watching sports, do you ever become so involved in the game that you react as if you were one of the players?		0.43**
16. Do you ever become so involved in a daydream that you are not aware of things happening around you?	INVOL	0.56**
17. Do you ever have dreams that are so real that you feel disoriented when you awake?	INVOL	0.50**
18. When playing sports, do you become so involved in the game that you lose track of time?	FOCUS	0.46**
19. Are you easily disturbed when working on a task?		−0.03
20. How well do you concentrate on enjoyable activities?		0.49**
21. How often do you play arcade or video games? (OFTEN should be taken to mean every day or every two days, on average.)	GAMES	0.35**

Item Stems	Subscale	*ITCorr*
22. How well do you concentrate on disagreeable tasks?		0.29**
23. Have you ever gotten excited during a chase or fight scene on TV or in the movies?	FOCUS	0.51**
24. To what extent have you dwelled on personal problems in the last 48 hours?		−0.10
25. Have you ever gotten scared by something happening on a TV show or in a movie?	INVOL	0.42**
26. Have you ever remained apprehensive or fearful long after watching a scary movie?	INVOL	0.31**
27. Do you ever avoid carnival or fairground rides because they are too scary?		−0.05
28. How frequently do you watch TV soap operas or docu-dramas?		0.28**
29. Do you ever become so involved in doing something that you lose all track of time?	FOCUS	0.49**

Note. Subscales: INVOL = Tendency to become involved in activities, FOCUS = Tendency to maintain focus on current activities, GAMES = Tendency to play video games

Note. ITCorr = Pearson correlation coefficients between ITQ item scores and the ITQ Total Score.

*$p < 0.01$

**$p < 0.001$

3.4. Pre-exposure Questionnaire for Study 1

Before proceeding with the experiments we would appreciate if you could answer a few questions about yourself. In case of questions where options are ***provided please circle the appropriate option****.*

Age: _______________ (in years and months)

Gender: **Male** **Female**

Have you experienced a virtual environment before? **Yes** **No**

1. Over the last 10 years, how often you Travelled or Experienced (tick boxes):

	Never	1 to 4 trips	5 to 10 trips	11 or more trips
Cars				
Buses or Coaches				
Trains				
Aircraft				
Small boats				
Ships, e.g. Channel ferries				
Swings				
Roundabouts: playgrounds				
Big dippers, funfair rides				

2. Over the last 10 years, how often you Felt Sick or Nauseated (tick boxes):

	Never	Rarely	Sometimes	Frequently	Always
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small boats					
Ships, e.g. Channel ferries					
Swings					
Roundabouts: playgrounds					
Big dippers, funfair rides					

3. **Over the last 10 years, how often you Vomited (tick boxes):**

	Never	Rarely	Sometimes	Frequently	Always
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small boats					
Ships, e.g. Channel ferries					
Swings					
Roundabouts: playgrounds					
Big dippers, funfair rides					

Please circle an option from a scale of 0 to 6 that best describes your answer to the following questions.

4. **Do you ever get extremely involved in projects that are assigned to you by your boss or your instructor, to the exclusion of other tasks?**

Never 0 1 2 3 4 5 6 Always

5. **How easily can you switch your attention from the task in which you are currently involved to a new task?**

Not easily 0 1 2 3 4 5 6 Very easily

6. **How frequently do you get emotionally involved (angry, sad, or happy) in the news stories that you read or hear?**

Never 0 1 2 3 4 5 6 Always

7. **How well do you feel today?**

Not well 0 1 2 3 4 5 6 Very well

8. **Do you easily become deeply involved in movies or TV dramas?**

Not easily 0 1 2 3 4 5 6 Very easily

9. **Do you ever become so involved in a television program or book that people have problems getting your attention?**

Never 0 1 2 3 4 5 6 Always

10. How mentally alert do you feel at the present time?

Not alert	0	1	2	3	4	5	6	Very alert

11. Do you ever become so involved in a movie that you are not aware of things happening around you?

Never	0	1	2	3	4	5	6	Always

12. How frequently do you find yourself closely identifying with the characters in a story line?

Never	0	1	2	3	4	5	6	Always

13. How physically fit do you feel today?

Not fit	0	1	2	3	4	5	6	Very fit

14. How good are you at blocking out external distractions when you are involved in something?

Not good	0	1	2	3	4	5	6	Very good

15. When watching sports, do you ever become so involved in the game that you react as if you were one of the players?

Never	0	1	2	3	4	5	6	Always

16. Do you ever become so involved in a daydream that you are not aware of things happening around you?

Never	0	1	2	3	4	5	6	Always

17. Do you ever have dreams that are so real that you feel disoriented when you awake?

Never	0	1	2	3	4	5	6	Always

18. When playing sports, do you become so involved in the game that you lose track of time?

Never	0	1	2	3	4	5	6	Always

19. Are you easily disturbed when working on a task?

Not easily	0	1	2	3	4	5	6	Very easily

20. How well do you concentrate on enjoyable activities?

Not well	0	1	2	3	4	5	6	Very well

21. How often do you play arcade or video games? (*Frequently should be taken to mean every day or every two days, on average*.)

Rarely	0	1	2	3	4	5	6	Frequently

22. Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?

Never	0	1	2	3	4	5	6	Always

23. How well do you concentrate on disagreeable tasks?

Not well	0	1	2	3	4	5	6	Very well

24. Have you ever gotten excited during a chase or fight scene on TV or in the movies?

Never	0	1	2	3	4	5	6	Always

25. To what extent have you dwelled on personal problems in the last 48 hours?

Not at all	0	1	2	3	4	5	6	Very much

26. Have you ever gotten scared by something happening on a TV show or in a movie?

Never	0	1	2	3	4	5	6	Always

27. Have you ever remained apprehensive or fearful long after watching a scary movie?

Never	0	1	2	3	4	5	6	Always

28. Do you ever avoid carnival or fairground rides because they are too scary?

Never	0	1	2	3	4	5	6	Always

29. How frequently do you watch TV soap operas or docu-dramas?

Rarely	0	1	2	3	4	5	6	Frequently

30. Do you ever become so involved in doing something that you lose all track of time?

Never	0	1	2	3	4	5	6	Always

31. How often have you used joysticks for example to play video games?

Rarely	0	1	2	3	4	5	6	Frequently

3.5. Post-exposure Questionnaire for Study 1

*Please circle an option from a scale of 0 to 3, that best describes the extent to which you feel the following symptoms (**0=no symptoms** to **3 = moderate symptoms**).*

1. **General discomfort**	0	1	2	3
2. **Fatigue**	0	1	2	3
3. **Headache**	0	1	2	3
4. **Eyestrain**	0	1	2	3
5. **Difficulty focusing**	0	1	2	3
6. **Increased salivation**	0	1	2	3
7. **Sweating**	0	1	2	3
8. **Nausea**	0	1	2	3
9. **Difficulty concentrating**	0	1	2	3
10. **Fullness of head**	0	1	2	3
11. **Blurred vision**	0	1	2	3
12. **Dizzy (eyes open)**	0	1	2	3
13. **Dizzy (eyes closed)**	0	1	2	3
14. **Vertigo**	0	1	2	3
15. **Stomach awareness**	0	1	2	3
16. **Burping**	0	1	2	3

*Based on your experience of the experiments conducted in the Sound room today, please circle an option from a scale of 0 to 6 that best describes your answer to the following questions (**0=not/no** to **3=moderate** to **6=very/completely**).*

17. **How much were you able to control events?**

Not able	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**Very able**

18. How responsive was the environment to actions that you initiated (or performed)?

Not responsive	0	1	2	3	4	5	6	Very responsive

19. How natural did your interactions with the environment seem?

Not natural	0	1	2	3	4	5	6	Very natural

20. How completely were all of your senses engaged?

Not engaged	0	1	2	3	4	5	6	Completely engaged

21. How much did the visual aspects of the environment involve you?

Not involve	0	1	2	3	4	5	6	Completely involve

22. How much did the auditory aspects of the environment involve you?

Not involve	0	1	2	3	4	5	6	Completely involve

23. How natural was the mechanism which controlled movement through the environment?

Not natural	0	1	2	3	4	5	6	Very natural

24. How aware were you of events occurring in the real world around you?

Not aware	0	1	2	3	4	5	6	Very aware

25. How aware were you of your display and control devices?

Not aware	0	1	2	3	4	5	6	Very aware

26. How compelling was your sense of objects moving through space?

Not compelling	0	1	2	3	4	5	6	Very compelling

27. How inconsistent (or disconnected) was the information coming from your various senses?

Not inconsistent	0	1	2	3	4	5	6	Very inconsistent

28. How much did your experiences in the virtual environment seem consistent with your real-world experiences?

Not consistent	0	1	2	3	4	5	6	Very consistent

29. Were you able to anticipate what would happen next in response to the actions that you performed?

Not able	0	1	2	3	4	5	6	Very able

30. How completely were you able to actively survey or search the environment using vision?

Not able	0	1	2	3	4	5	6	Very able

31. How well could you identify sounds?

Not well	0	1	2	3	4	5	6	Very well

32. How well could you localize sounds?

Not well	0	1	2	3	4	5	6	Very well

33. How compelling was your sense of moving around inside the virtual environment?

Not compelling	0	1	2	3	4	5	6	Very compelling

34. How closely were you able to examine objects?

Not closely	0	1	2	3	4	5	6	Very closely

35. To what degree did you feel confused (or disoriented) at the beginning of breaks or at the end of the experimental session?

Not confused	0	1	2	3	4	5	6	Very confused

36. How involved were you in the virtual environment experience?

Not involved	0	1	2	3	4	5	6	Very involved

37. How distracting was the control mechanism?

Not distracting	0	1	2	3	4	5	6	Very distracting

38. How much delay did you experience between your actions and expected outcomes?

No delay	0	1	2	3	4	5	6	Very much delay

39. How quickly did you adjust to the virtual environment experience?

Not quickly	0	1	2	3	4	5	6	Very quickly

40. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

Not proficient	0	1	2	3	4	5	6	Very proficient

41. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

Not interfere	0	1	2	3	4	5	6	Very much interfere

42. How much did the control devices interfere with the performance of assigned tasks or with other activities?

Not interfere	0	1	2	3	4	5	6	Very much interfere

43. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

Not well	0	1	2	3	4	5	6	Very well

44. Did you learn new techniques that enabled you to improve your performance?

Not learn	0	1	2	3	4	5	6	Very much learn

45. Were you involved in the experimental task to the extent that you lost track of time?

Not involved	0	1	2	3	4	5	6	Very involved

Please illustrate if you were liked or disliked any facility of the sound room.

____

____

____

Please illustrate if you found any sections of the questionnaires difficult to understand.

____

____

____

Appendix 4: Presentation Order for Study 1

4.1. Presentation Sequence of the Experimental Conditions for Study 1

	Experimental Conditions					
Sequence	**1**	**2**	**3**	**4**	**5**	**6**
1	1A	1B	3B	2A	3A	2B
2	1B	2A	1A	2B	3B	3A
3	2A	2B	1B	3A	1A	3B
4	2B	3A	2A	3B	1B	1A
5	3A	3B	2B	1A	2A	1B
6	3B	1A	3A	1B	2B	2A

Appendix 5: Presentation Order for Study 2

5.1. Presentation Sequence for Study 2. 1 to 15 = sound ID, L/R = left/right direction, A/B/C = arrival time 1/2/3.

	Experimental conditions																														
Sequence	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
1	10LA	11LB	3RC	10RA	1RA	4LA	8RB	6RC	2RB	12RC	8LB	1LA	7LA	2LB	14LB	11RB	9LC	13RA	7RA	12LC	5LB	5RB	4RA	15LC	13LA	3LC	15RC	9RC	6LC	14RB	1LA
2	11LC	10RB	10LB	4LB	3RA	6RA	1RB	12RA	8RC	1LB	2RC	2LC	8LC	11RC	7LB	13RB	14LC	12LA	9LA	5RC	7RB	15LA	5LC	3LA	4RB	9RA	13LB	14RC	15RA	1LB	6LA
3	10RC	4LC	11LA	6RB	10LC	12RB	3RB	1LC	1RC	2LA	8RA	11RA	2RA	13RC	8LA	12LB	7LC	5RA	14LA	15LB	9LB	3LB	7RC	9RB	5LA	14RA	4RC	1LC	13LC	6LB	15RB
4	4LA	6RC	10RA	12RC	11LB	1LA	10LA	2LB	3RC	11RB	1RA	13RA	8RB	12LC	2RB	5RB	8LB	15LC	7LA	3LC	14LB	9RC	9LC	14RB	7RA	1LA	5LB	6LC	4RA	15RC	13LA
5	6RA	12RA	4LB	1LB	10RB	2LC	11LC	11RC	10LB	13RB	3RA	12LA	1RB	5RC	8RC	15LA	2RC	3LA	8LC	9RA	7LB	14RC	14LC	1LB	9LA	6LA	7RB	15RA	5LC	13LB	4RB
6	12RB	1LC	6RB	2LA	4LC	11RA	10RC	13RC	11LA	12LB	10LC	5RA	3RB	15LB	1RC	3LB	8RA	9RB	2RA	14RA	8LA	1LC	7LC	6LB	14LA	15RB	9LB	13LC	7RC	4RC	5LA
7	1LA	2LB	12RC	11RB	6RC	13RA	4LA	12LC	10RA	5RB	11LB	15LC	10LA	3LC	3RC	9RC	1RA	14RB	8RB	1LA	2RB	6LC	8LB	15RC	7LA	13LA	14LB	4RA	9LC	5LB	7RA
8	2LC	11RC	1LB	13RB	12RA	12LA	6RA	5RC	4LB	15LA	10RB	3LA	11LC	9RA	10LB	14RC	3RA	1LB	1RB	6LA	8RC	15RA	2RC	13LB	8LC	4RB	7LB	5LC	14LC	7RB	9LA
9	11RA	13RC	2LA	12LB	1LC	5RA	12RB	15LB	6RB	3LB	4LC	9RB	10RC	14RA	11LA	1LC	10LC	6LB	3RB	15RB	1RC	13LC	8RA	4RC	2RA	5LA	8LA	7RC	7LC	9LB	14LA
10	13RA	12LC	11RB	5RB	2LB	15LC	1LA	3LC	12RC	9RC	6RC	14RB	4LA	1LA	10RA	6LC	11LB	15RC	10LA	13LA	3RC	4RA	1RA	5LB	8RB	7RA	2RB	9LC	8LB	14LB	7LA
11	12LA	5RC	13RB	15LA	11RC	3LA	2LC	9RA	1LB	14RC	12RA	1LB	6RA	6LA	4LB	15RA	10RB	13LB	11LC	4RB	10LB	5LC	3RA	7RB	1RB	9LA	8RC	14LC	2RC	7LB	8LC
12	5RA	15LB	12LB	3LB	13RC	9RB	11RA	14RA	2LA	1LC	1LC	6LB	12RB	15RB	6RB	13LC	4LC	4RC	10RC	5LA	11LA	7RC	10LC	9LB	3RB	14LA	1RC	7LC	8RA	8LA	2RA
13	15LC	3LC	5RB	9RC	12LC	14RB	13RA	1LA	11RB	6LC	2LB	15RC	1LA	13LA	12RC	4RA	6RC	5LB	4LA	7RA	10RA	9LC	11LB	14LB	10LA	7LA	3RC	8LB	1RA	2RB	8RB
14	3LA	9RA	15LA	14RC	5RC	1LB	12LA	6LA	13RB	15RA	11RC	13LB	2LC	4RB	1LB	5LC	12RA	7RB	6RA	9LA	4LB	14LC	10RB	7LB	11LC	8LC	10LB	2RC	3RA	8RC	1RB
15	9RB	14RA	3LB	1LC	15LB	6LB	5RA	15RB	12LB	13LC	13RC	4RC	11RA	5LA	2LA	7RC	1LC	9LB	12RB	14LA	6RB	7LC	4LC	8LA	10RC	2RA	11LA	8RA	10LC	1RC	3RB
16	14RB	1LA	9RC	6LC	3LC	15RC	15LC	13LA	5RB	4RA	12LC	5LB	13RA	7RA	11RB	9LC	2LB	14LB	1LA	7LA	12RC	8LB	6RC	2RB	4LA	8RB	10RA	1RA	11LB	3RC	10LA
17	1LB	6LA	14RC	15RA	9RA	13LB	3LA	4RB	15LA	5LC	5RC	7RB	12LA	9LA	13RB	14LC	11RC	7LB	2LC	8LC	1LB	2RC	12RA	8RC	6RA	1RB	4LB	3RA	10RB	10LB	11LC
18	6LB	15RB	1LC	13LC	14RA	4RC	9RB	5LA	3LB	7RC	15LB	9LB	5RA	14LA	12LB	7LC	13RC	8LA	11RA	2RA	2LA	8RA	1LC	1RC	12RB	3RB	6RB	10LC	4LC	11LA	10RC
19	15RC	13LA	6LC	4RA	1LA	5LB	14RB	7RA	9RC	9LC	3LC	14LB	15LC	7LA	5RB	8LB	12LC	2RB	13RA	8RB	11RB	1RA	2LB	3RC	1LA	10LA	12RC	11LB	6RC	10RA	4LA
20	13LB	4RB	15RA	5LC	6LA	7RB	1LB	9LA	14RC	14LC	9RA	7LB	3LA	8LC	15LA	2RC	5RC	8RC	12LA	1RB	13RB	3RA	11RC	10LB	2LC	11LC	1LB	10RB	12RA	4LB	6RA
21	4RC	5LA	13LC	7RC	15RB	9LB	6LB	14LA	1LC	7LC	14RA	8LA	9RB	2RA	3LB	8RA	15LB	1RC	5RA	3RB	12LB	10LC	13RC	11LA	11RA	10RC	2LA	4LC	1LC	6RB	12RB
22	5LB	7RA	4RA	9LC	13LA	14LB	15RC	7LA	6LC	8LB	1LA	2RB	14RB	8RB	9RC	1RA	3LC	3RC	15LC	10LA	5RB	11LB	12LC	10RA	13RA	4LA	11RB	6RC	2LB	12RC	1LA
23	7RB	9LA	5LC	14LC	4RB	7LB	13LB	8LC	15RA	2RC	6LA	8RC	1LB	1RB	14RC	3RA	9RA	10LB	3LA	11LC	15LA	10RB	5RC	4LB	12LA	6RA	13RB	12RA	11RC	1LB	2LC
24	9LB	14LA	7RC	7LC	5LA	8LA	4RC	2RA	13LC	8RA	15RB	1RC	6LB	3RB	1LC	10LC	14RA	11LA	9RB	10RC	3LB	4LC	15LB	6RB	5RA	12RB	12LB	1LC	13RC	2LA	11RA
25	14LB	7LA	9LC	8LB	7RA	2RB	5LB	8RB	4RA	1RA	13LA	3RC	15RC	10LA	6LC	11LB	1LA	10RA	14RB	4LA	9RC	6RC	3LC	12RC	15LC	1LA	5RB	2LB	12LC	11RB	13RA
26	7LB	8LC	14LC	2RC	9LA	8RC	7RB	1RB	5LC	3RA	4RB	10LB	13LB	11LC	15RA	10RB	6LA	4LB	1LB	6RA	14RC	12RA	9RA	1LB	3LA	2LC	15LA	11RC	5RC	13RB	12LA
27	8LA	2RA	7LC	8RA	14LA	1RC	9LB	3RB	7RC	10LC	5LA	11LA	4RC	10RC	13LC	4LC	15RB	6RB	6LB	12RB	1LC	1LC	14RA	2LA	9RB	11RA	3LB	13RC	15LB	12LB	5RA
28	2RB	8RB	8LB	1RA	7LA	3RC	14LB	10LA	9LC	11LB	7RA	10RA	5LB	4LA	4RA	6RC	13LA	12RC	15RC	1LA	6LC	2LB	1LA	11RB	14RB	13RA	9RC	12LC	3LC	5RB	15LC
29	8RC	1RB	2RC	3RA	8LC	10LB	7LB	11LC	14LC	10RB	9LA	4LB	7RB	6RA	5LC	12RA	4RB	1LB	13LB	2LC	15RA	11RC	6LA	13RB	1LB	12LA	14RC	5RC	9RA	15LA	3LA
30	1RC	3RB	8RA	10LC	2RA	11LA	8LA	10RC	7LC	4LC	14LA	6RB	9LB	12RB	7RC	1LC	5LA	2LA	4RC	11RA	13LC	13RC	15RB	12LB	6LB	5RA	1LC	15LB	14RA	3LB	9RB
31	3RC	10LA	1RA	11LB	8RB	10RA	2RB	4LA	8LB	6RC	7LA	12RC	14LB	1LA	9LC	2LB	7RA	11RB	5LB	13RA	4RA	12LC	13LA	5RB	15RC	15LC	6LC	3LC	1LA	9RC	14RB

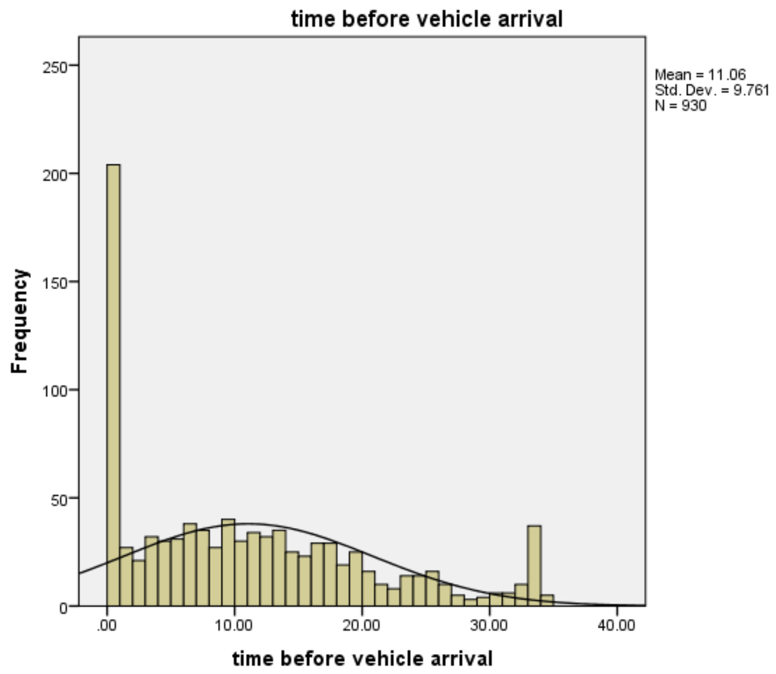
Appendix 6: Preliminary Tests on the Data Obtained in Study 2

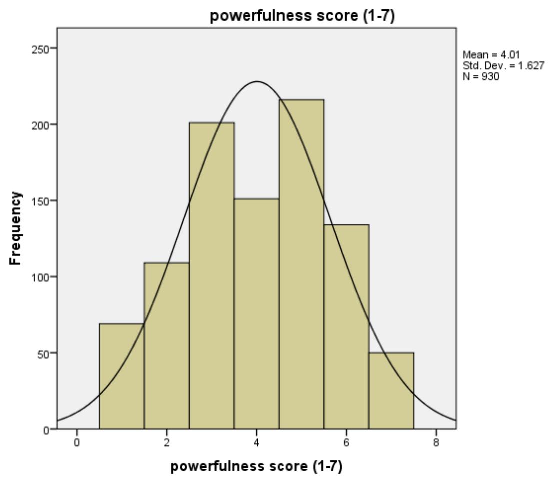
6.1. Normality tests for measures collected across all experimental conditions.

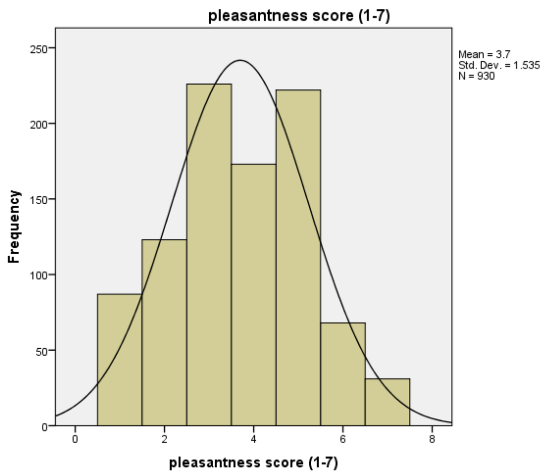
Statistics				
		time before vehicle arrival	powerfulness score (1-7)	pleasantness score (1-7)
N	Valid	930	930	930
	Missing	60	60	60
Minimum		0.00	1	1
Maximum		34.48	7	7
Mean		11.0592	4.01	3.70
Std. Error of Mean		.32009	.053	.050
Median		9.3800	4.00	4.00
Mode		0.00	5	3
Std. Deviation		9.76139	1.627	1.535
Skewness		.725	-.090	.018
Std. Error of Skewness		.080	.080	.080
Kurtosis		-.341	-.853	-.683
Std. Error of Kurtosis		.160	.160	.160
Z score of skewness		9.06	-1.13	.225
Z score of kurtosis		-2.13	-5.31	-4.26

Usually for large sample, z-scores < 2.58 is applied. However, here N > 200, therefore z-score criterion was not a requirement and histograms were checked.

Histograms showed that the data was normally distributed except for a skewness in time-before-vehicle arrival.







6.2. Test for homogeneity of variance

Levene's Test of Equality of Error Variances[a]				
	F	df1	df2	Sig.
powerfulness score (1-7)	.142	2	927	.868
pleasantness score (1-7)	.619	2	927	.539
time before vehicle arrival	2.903	2	927	.055

a. Design: Intercept + participant + arrival_time

Since p > .05 in all cases therefore, the assumption that variances are equal across all levels is satisfied.

6.3. Test for independence of covariate (participant ID) and independent variable (vehicle's arrival time).

Arrival time had no significant effect on the participant ID, $F(2, 927) = 0.00$, $p = 1.0$. Thus, assumption of independence of covariate and independent variable was not violated.

6.4. Test for homogeneity of regression slopes

Multivariate independent group ANCOVA were performed using arrival time as the independent variable, participant ID as the covariate, and powerfulness, pleasantness and time-before-vehicle-arrival as dependent variables.

It showed that there was no significant interaction ($p < .05$) between the effects of arrival time and participant ID on:

I. Powerfulness: $F(2, 924) = .129$, $p =.88$

II. Pleasantness: $F(2, 924) = .946$, $p =.39$

III. Time-before-vehicle-arrival: $F(2, 924) = .142$, $p =.87$

Appendix 7: Metrics of Ambient Soundscapes used in Study 3

7.1. Table showing mean dB(A)$_{eq}$ of ambient sounds for each participant and every experimental condition

Participant ID	Experimental Condition						
	1	2	3	4	5	6	7
1	45	50	48	48	52	49	48
2	51	51	57	57	48	48	50
3	48	48	52	50	52	56	51
4	58	51	53	48	47	48	51
5	49	50	47	52	51	48	47
6	51	47	47	53	47	47	47
7	46	46	49	47	47	48	46
8	47	45	48	50	47	50	44
9	46	47	47	46	48	47	46
10	51	51	50	52	47	42	51
11	43	42	45	44	48	45	46
12	48	49	44	43	40	45	47
13	50	45	50	50	49	46	50
14	44	45	44	47	47	45	52

Appendix 8: Presentation Order for Study 3

8.1. Presentation Sequence of the Experimental Conditions for Study 3

	Experimental Conditions						
Sequence	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1A	3B	2A	1A	1B	2B	3A
2	3B	1A	1A	2B	2A	3A	1B
3	1A	2B	3B	3A	1A	1B	2A
4	2B	3A	1A	1B	3B	2A	1A
5	3A	1B	2B	2A	1A	1A	3B
6	1B	2A	3A	1A	2B	3B	1A
7	2A	1A	1B	3B	3A	1A	2B

Appendix 9: Preliminary Tests on the Data Obtained in Study 3

9.1. Normality tests for measures collected across all experimental conditions.

	Mean	SE of Mean	SD	Skew -ness	SE of Skew -ness	Kurt -osis	SE of Kurt-osis	z-score of skewness	z-score of kurtosis
Detection distance for condition 1	48.81	5.42	20.28	0.59	0.60	0.84	1.15	0.99	0.72
Recognis-ability for condition 1	4.46	0.33	1.23	-1.27	0.60	1.55	1.15	**-2.13**	1.34
Detectability for condition 1	4.21	0.41	1.54	-0.62	0.60	-0.75	1.15	-1.04	-0.65
Powerfulness for condition 1	3.21	0.36	1.34	-0.20	0.60	-1.24	1.15	-0.34	-1.07
Pleasantness for condition 1	4.82	0.28	1.03	0.01	0.60	0.58	1.15	0.01	0.50
Detection distance for condition 2	61.55	7.18	26.85	0.95	0.60	0.99	1.15	1.59	0.86
Recognis-ability for condition 2	4.50	0.40	1.51	-0.39	0.60	-0.56	1.15	-0.66	-0.49
Detectability for condition 2	4.93	0.41	1.54	-0.74	0.60	-0.78	1.15	-1.24	-0.68
Powerfulness for condition 2	3.64	0.37	1.39	0.95	0.60	1.25	1.15	1.59	1.08
Pleasantness for condition 2	4.36	0.37	1.39	0.24	0.60	-0.43	1.15	0.41	-0.37
Detection distance for condition 3	46.16	5.42	20.27	1.14	0.60	1.68	1.15	1.91	1.46
Recognis-ability for condition 3	4.71	0.42	1.59	-0.79	0.60	0.78	1.15	-1.33	0.68

Detectability for condition 3	4.57	0.50	1.87	-0.91	0.60	0.04	1.15	-1.53	0.04
Powerfulness for condition 3	3.36	0.37	1.39	0.24	0.60	-0.43	1.15	0.41	-0.37
Pleasantness for condition 3	4.64	0.40	1.50	0.08	0.60	-0.63	1.15	0.13	-0.54
Detection distance for condition 4	48.29	5.17	19.33	0.00	0.60	-0.11	1.15	0.00	-0.10
Recognis-ability for condition 4	4.79	0.41	1.53	-0.18	0.60	-0.78	1.15	-0.31	-0.68
Detectability for condition 4	4.29	0.44	1.64	0.20	0.60	-1.26	1.15	0.34	-1.09
Powerfulness for condition 4	3.79	0.35	1.31	0.46	0.60	-0.75	1.15	0.77	-0.65
Pleasantness for condition 4	4.93	0.30	1.14	0.52	0.60	0.12	1.15	0.87	0.11
Detection distance for condition 5	44.43	5.86	21.91	-0.76	0.60	-0.26	1.15	-1.27	-0.23
Recognis-ability for condition 5	4.29	0.29	1.07	-0.22	0.60	0.67	1.15	-0.38	0.58
Detectability for condition 5	4.64	0.32	1.22	-0.69	0.60	0.10	1.15	-1.15	0.09
Powerfulness for condition 5	3.79	0.33	1.25	0.19	0.60	-1.10	1.15	0.32	-0.95
Pleasantness for condition 5	4.79	0.37	1.37	0.24	0.60	-0.91	1.15	0.40	-0.79
Detection distance for condition 6	35.06	5.70	21.34	-0.39	0.60	-0.66	1.15	-0.65	-0.57
Recognis-ability for condition 6	4.21	0.38	1.42	-0.25	0.60	-1.26	1.15	-0.42	-1.09
Detectability for condition 6	3.86	0.46	1.70	-0.40	0.60	-0.74	1.15	-0.66	-0.65
Powerfulness for condition 6	3.29	0.37	1.38	0.42	0.60	-1.85	1.15	0.70	-1.60
Pleasantness for condition 6	4.64	0.32	1.22	0.21	0.60	-0.47	1.15	0.35	-0.41

Detection distance for condition 7	26.41	6.56	24.53	1.82	0.60	4.18	1.15	3.05	3.63
Recognis-ability for condition 7	4.04	0.43	1.60	-0.31	0.60	-0.84	1.15	-0.51	-0.73
Detectability for condition 7	3.79	0.43	1.60	0.11	0.60	-1.19	1.15	0.19	-1.03
Powerfulness for condition 7	3.50	0.31	1.14	0.09	0.60	-0.75	1.15	0.15	-0.65
Pleasantness for condition 7	4.46	0.23	0.87	0.75	0.60	1.43	1.15	1.26	1.24
Detection distance for condition 8	44.70	11.43	42.76	0.82	0.60	-0.70	1.15	1.37	-0.61
Recognis-ability for condition 8	3.57	0.39	1.45	0.89	0.60	0.87	1.15	1.49	0.75
Detectability for condition 8	3.71	0.32	1.20	-0.28	0.60	1.30	1.15	-0.47	1.13
Powerfulness for condition 8	3.21	0.39	1.48	0.24	0.60	-0.40	1.15	0.40	-0.35
Pleasantness for condition 8	3.50	0.39	1.45	-0.53	0.60	-0.86	1.15	-0.88	-0.75
Detection distance for condition 9	34.31	5.96	22.28	0.51	0.60	0.05	1.15	0.86	0.04
Recognis-ability for condition 9	3.71	0.47	1.77	0.12	0.60	-0.49	1.15	0.20	-0.43
Detectability for condition 9	4.43	0.20	0.76	-0.97	0.60	-0.35	1.15	-1.62	-0.30
Powerfulness for condition 9	4.07	0.38	1.44	0.04	0.60	-1.39	1.15	0.06	-1.21
Pleasantness for condition 9	3.79	0.30	1.12	-0.28	0.60	-1.31	1.15	-0.46	-1.14
Detection distance for condition 10	24.34	5.69	21.31	0.69	0.60	-0.58	1.15	1.15	-0.50
Recognis-ability for condition 10	4.36	0.45	1.69	0.01	0.60	-0.83	1.15	0.02	-0.72
Detectability for condition 10	3.93	0.38	1.44	1.05	0.60	0.27	1.15	1.75	0.23

Powerfulness for condition 10	3.43	0.39	1.45	0.52	0.60	-0.07	1.15	0.86	-0.06
Pleasantness for condition 10	4.00	0.38	1.41	0.00	0.60	1.36	1.15	0.00	1.18
Detection distance for condition 11	35.27	8.28	30.97	0.36	0.60	-1.68	1.15	0.60	-1.46
Recognis-ability for condition 11	3.21	0.39	1.48	0.57	0.60	-0.67	1.15	0.96	-0.58
Detectability for condition 11	4.50	0.34	1.29	-0.13	0.60	0.36	1.15	-0.21	0.31
Powerfulness for condition 11	3.64	0.25	0.93	0.19	0.60	-0.79	1.15	0.31	-0.68
Pleasantness for condition 11	4.21	0.39	1.48	-0.26	0.60	-1.55	1.15	-0.44	-1.34
Detection distance for condition 12	26.75	5.25	19.65	0.50	0.60	-1.11	1.15	0.83	-0.96
Recognis-ability for condition 12	3.79	0.28	1.05	0.03	0.60	-1.50	1.15	0.05	-1.30
Detectability for condition 12	4.86	0.31	1.17	-1.37	0.60	1.82	1.15	-2.30	1.58
Powerfulness for condition 12	3.64	0.32	1.22	-0.69	0.60	0.10	1.15	-1.15	0.09
Pleasantness for condition 12	3.57	0.40	1.50	-0.08	0.60	-1.12	1.15	-0.14	-0.97

Here, all z-scores except recognisability at condition 1 < 1.96; and all z-scores < 2.58. Therefore, z-score criterion is satisfied for all data therefore the condition of normal distribution of data is met.