Applied Acoustics 185 (2022) 108412

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Howl, whirr, and whistle: The perception of electric powertrain noise and its importance for perceived quality in electrified vehicles

Mara Münder [a,b,*], Claus-Christian Carbon [c,b]

[a] BMW Group, Munich 80788, Knorrstraße 147, Germany
[b] Bamberg Graduate School of Affective and Cognitive Sciences (BaGrACS), Bamberg 96047, Kapuzinerstraße 16, Germany
[c] Department of General Psychology and Methodology, University of Bamberg, Bamberg 96047, Markusplatz 3, Germany

ARTICLE INFO

Article history:
Received 20 May 2021
Received in revised form 9 August 2021
Accepted 3 September 2021
Available online 21 September 2021

Keywords:
Ambient 3D Sound
Perceived Quality
Electric Powertrain Noise
Acoustic Simulator
NVH
Association Principle

ABSTRACT

The technical specifications of electrified vehicles (xEVs) will drastically change the way future vehicles might sound compared to conventional vehicles with internal combustion engines (ICEVs). The electrified powertrain is responsible for a profoundly different profile in vibro-acoustical characteristics (NVH: noise, vibration, and harshness) and offers the opportunity to create specific sounds related to certain requirements and endorsing associations for increasing the user experience and aesthetic appreciation. The present study's main aim was to evaluate the perceived emergence of the electric powertrain noise and its implications for perceived quality conveyed by it. Utilizing a sophisticated acoustic simulator presenting ambisonic 3D stimuli from eleven different electrified cars in four different driving scenarios, $N = 65$ participants evaluated the perceptibility of e-powertrain noise and perceived quality of the vehicle's interior soundscape. We revealed the auditory modality as an integral part of assessing the product's quality and gathered qualitative reference points for further investigations.

1. Introduction

As eco-friendly mobility becomes an increasingly societal objective, technical progress and competitive pressure drive the electrification of vehicles. The progression to alternative powertrains presents manifold challenges to the automobile industries and can be described as non-linear and disruptive development [1]. Due to a radically different acoustical profile of xEVs (generic term subsuming any kind of electrified vehicle) compared to the conventional internal combustion engine vehicles (ICEVs), versatile questions in the development of vehicle acoustics are posed. Facing these changes, acoustic engineers are challenged with reconsidering the optimization process of the differently shaped vibro-acoustical phenomena [2,3], commonly subsumed under the umbrella term *NVH* (Noise, Vibration, and Harshness). As a main source of various NVH phenomena [4] the vehicle's powertrain holds a key role in the context of acoustical refinement in xEVs.

How we perceive and experience a vehicle is based on multiple variables, which can be differentiated in the degree of their immediate perceptibility. Multisensory information of the product's characteristics is perceived by our different perception modalities and contribute to the overall, the *holistic* experience [5]. Aside from the visual appearance conveyed to the observer by the vehicle's shape and design, its sound and vibro-acoustical characteristics are the most immediate perceptible features and, therefore, vital components in terms of customer satisfaction [2,4,6,7].

The present contribution mainly focuses on the driver's perception of e-powertrain noise and its implications for the quality impression conveyed by it to better estimate its importance in terms of overall customer satisfaction. To do justice to the experiential side of e-powertrain noise, we pursued a methodological approach which is based on a psychophysics testing framework. We followed a Path #2-testing strategy according to Carbon [8]: We employed a typical car driving context by situating participants in a real car equipped with immersive 3D ambisonic sound capabilities; this leads to ecologically valid testing while preserving the controllability of a lab-based experimental setup.

2. Theoretical background

The resulting implications from powertrain electrification are manifold for both – exterior and interior noise. With the driver's acoustic experience being the focal point of the following contribution, we will be focusing on the interior soundscape. This is done

* Corresponding author at: BMW Group, Munich 80788, Knorrstraße 147, Germany.

E-mail address: Mara.Muender@bmw.de (M. Münder).

https://doi.org/10.1016/j.apacoust.2021.108412
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by first elaborating on the novel and radically different acoustic xEV profile. Subsequently, psychological constructs like perceived quality and associations and methods of assessing subjective data in listening tests will be considered in a differentiated manner.

2.1. Acoustic profile of the xEV

In the past decades, the acoustic quality of vehicles steadily improved in terms of an overall reduced sound pressure level (SPL) [2]. With the shift from conventional powertrains to electric powertrain concepts, we inherently observe a new, abrupt decrease and change in the overall noise emission. When comparing xEVs with ICEVs, the powertrain configuration has the most extensive implications regarding the resulting noise emission and NVH characteristics, which are often described as howling, whirring, or whistling. The much more muted powertrain concepts can lead to an up to 20 dB lower SPL(A-weighted) in full acceleration mode in xEVs than in comparable ICEVs, according to Blickensdorff et al. [9]. This opens opportunities to creating vehicles in an acoustically novel way, offering extraordinarily pleasing and quiet interior soundscapes with potentially high acoustic comfort. This relative quietness comes at a price as the low absent powertrain noise might even *unmask* various disturbing noises like external noise, wind and tire noise or whining and whistling from auxiliaries and power electronics [3,9,10]. Those sources of noise might have never been perceived as being problematic, disturbing, or irritating in a much louder conventional sound context of ICEVs. Still, now, being unmasked in the xEV's sound profile, the interfering noises possibly need to be reassessed and probably also be optimized in the long run [2].

Not only has the SPL changed but the characteristics of the whole sound profile. Actually, the acoustic profile of xEVs significantly deviates from the one of ICEVs: Instead of the ICE-typical broadband noise spectrum, which is dominated by engine orders and its harmonics in the frequency range below 1 kHz, e-powertrain noise is characterized by higher frequencies and tonal components in the subjectively relevant range from 1 to 10 kHz, for which the human hearing apparatus is particularly sensitive [9,10]. The noise in xEVs is often accompanied by relatively stronger wind and tire noise. Electric powertrains show characteristic switching noise caused by the power electronics, also known as Pulse Width Modulation (PWM), usually varying in the frequency range from 250 Hz to 20 kHz. Research about the discomfort this might induce is still rare, but such switching noise might be perceived as quite unpleasant [11]. As found by psychoacoustic investigations [12–14], the significantly quieter xEVs are potentially more annoying and less acceptable from a customer's viewpoint since their acoustic profile is characterized by higher frequencies and tonal components.

2.2. Perception of e-powertrain noise

Considering the specific acoustic profile of xEVs, which might be perceived as unfamiliar [9] and at times even as unpleasant and annoying [10,12], we focused on the perceptibility of e-powertrain noise and its impact on the overall quality impression conveyed by it. In contrast to physical metrics and technical-objective vehicle characteristics, as for example, performance parameters, we focus on the driver's perception and aesthetic appreciation of the vehicles' soundscape as they are mostly key to market-relevant dimensions such as comfort and overall product quality impression [5]. A soundscape is defined by the International Organization for Standardization in the ISO 12913-1 as an "acoustic environment as perceived or experienced and/or understood by a person or people, in context" [15]. This approach is considerably more challenging to address than merely using technical measurement on a test bench [16]. Nevertheless, especially specific interferences of noises, which become salient to human ears, but are hard to identify and localize by automatic routines, yet make this approach even more appealing. With NVH phenomena being immediately perceivable qualia, e-powertrain noise contributes to shaping the user's experience and thereby carries a large share of the overall customer satisfaction [2,4,7] and contributes to successful product development [17]. Thus, we want to gain insight into the relation of perceived e-powertrain noise and its associated overall product quality.

When it comes to the term *quality* in the context of acoustics, one can find a wide variety of definitions and approaches to this construct. Sound quality for instance, can be defined as the adequacy [18] or suitability [19] of a sound that is being emitted by a technical object, evolving from a process where multiple quality features are situationally compared to one another [20]. Genuit [21] suggests acoustic quality to be composed of three different influential aspects: 1) the *physical sound* (sound field), 2) *psychoacoustics* (auditory perception), and 3) (further) *psychological aspects* (auditory evaluation). As we focus on the driver's perception of e-powertrain noise and their individual subjective assessment of its conveyed product quality in this study, especially the so-called *psychological aspects,* play a vital role. These psychological aspects include affective, cognitive, and situational factors [17,22]. Altogether they contribute to an overall *percept* rather than just representing a mere sensory perception in the auditory apparatus [15]. According to Stylidis et al. [23], sound quality is a component of *technical perceived quality* (TPQ), which again is a subset of the *value-based perceived quality* (VPQ). The VPQ embodies the total customer experience taking the multimodal components of the TPQ such as visual, haptic, acoustic, and olfactory product attributes into account, as well as external factors [23]. In the realm of this paper, we will prefer the term *perceived quality*, which is conveyed by the acoustic scene, operationalized here by different e-powertrain examples. Related to the construct of sound quality, Genuit et al. [16] further mention the *object-related quality impression*, which emerges from specific product criteria in the sense of the sum of the object's quality itself. Referring to the axiom of Gestalt psychology – *the whole is greater than the sum of its parts* [24] – the quality impression conveyed by the vehicle's acoustic characteristics though is still only one part of a wholesome vehicle experience, serving a single modality. Pioneer perceptual scientist Gustav Theodor Fechner already proposed this Gestalt view in 1866: "the beauty of a whole [...] will [...] not [be] diminished but [...] increased in the way that the whole surpasses the parts" [25, p.7]. Different vehicle characteristics can be perceived via one or more perceptual channels and contribute to the overall constructs, such as vehicle comfort impression [1] or perceived product quality [23]. Eventually, the coherence of the general concept – the total vehicle – is most relevant. Still, to derive the potential for improvement, this general construct needs to be broken apart into the different perception facets and each assessed for themselves [16].

The auditory evaluation results in individual impressions, which are strongly modulated by memory associations – a central principle of cognitive sciences. In aesthetic theory, this idea is originating in Fechner's *Aesthetic Association Principle* (AAP) [25]: the impression of an object conveyed by a sensation – in our case, the acoustical scene conveyed by the vehicle and its e-powertrain – is ultimately linked to the individual's memory and former experience, as they are merged with the current sensation into a coherent percept. Though this principle is widely used in visual perception, Fechner also mentioned the capability of acoustics, regardless of whether it is music, a soundscape, or a distinct acoustic stimulus, to be utilized to create and guide certain associations [25]. For instance, there is strong evidence for music-to-color associations, which appear to primarily result from a common, mediating emotional association [26–30]. From Fechner's AAP [25] methods like the so-called ASIP (Associated Imaginations on Sound Perceptions) have been derived during the BRITE-Euram EU-Project 96-3727 "OBELICS" (Objective Evaluation of Interior Car Sound) as an approach to systematically analyze affective reactions to interior vehicle sound [31], as well as the EVE-method (Explorative Vehicle Evaluation) as a more practical approach to evaluate target sounds in their original on-road driving context [32]. Moreover, the work of Fiebig et al. [33] depicts recent research on how even subtle acoustic information – defining the contextual soundscape of the given environment – can influence the human affective response.

Another relevant and linked aspect is the consideration of individual factors when assessing subjectively perceived constructs confounded with affective, cognitive, and situational variables. Genuit and colleagues [16] highlighted the relevance of the individual frame of reference when acoustic events are evaluated, due to their comparison with former experiences, and bring on the term of *introspective matching*, which can be based on real experience, assumptions, expectations or also associations. For instance, driving a vehicle has been accompanied by the ICE-typical sound profile for decades for many people and thereby formed their horizon of experience. Customers thereby adapted to certain sound patterns in reference to different operational situations and now expect and associate specific patterns within their situational driving context. In conclusion, perceived quality is not an absolute measure due to its dependency on particular personal and contextual variables. Considering the novel acoustic profile of e-powertrains, with which most people are still quite unfamiliar with, it is essential to find out to what extent e-powertrain noise is related to the individual quality impression when it comes to reassessing this customer-relevant feature.

2.3. Methods to assess subjective measures in NVH development

In the field of vehicle acoustics, perceptual evaluation is pursued by a variety of methodological approaches. Classical approaches are laboratory listening tests, jury testing, semantic differentials, pairwise comparison, or ranking tasks, categorial evaluation, and magnitude estimations [16,34,35]. Strict laboratory and experimental listening tests (so-called Path #3 testing according to Carbon [8]) are predominantly used to assess psychoacoustic measures like loudness, sharpness, tonality, or roughness, but lacks ecological validity as it neglects contextual variables and does not do justice to the complexity of the listener's real-life-percept [16]. On the contrary, real vehicle testing (so-called Path #1 testing according to Carbon [8]) images the contextual variables of the real-life driving scenarios to the full extend and includes the factor of driver-vehicle interaction but lacks the standardization and reproducibility of testing conditions. For instance, approaches like the EVE-method (Explorative Vehicle Evaluation) aim to investigate on affective reactions and noise evaluations of the participants in the original context and thereby, create test surroundings close to reality [32]. Genuit et al. [16] suggested combining approved methods from the field of psychoacoustics with explorative approaches from the field of social sciences to evaluate vehicle acoustics in a standardized, controlled environment, yet taking evaluation relevant context factors into account. Especially when assessing complex constructs, such as the perceived quality of e-powertrain noise in dynamic use case scenarios, the consideration of various context factors is inevitable. As e-powertrain noise is a somewhat novel and uprising phenomenon, studies with subjective evaluations regarding perceived quality and customer satisfaction are relatively rare. For instance, a promising study is the jury testing for xEVs in wide open throttle conducted by Swart and Bekker [36], which provides insights on how the acoustic profiles have an impact on customer satisfaction and comfort evaluation. Here, participants evaluated the stimuli on a desktop computer in an anechoic chamber over headphones.

3. The present study

The main aim of the present study was to evaluate the e-powertrain noise of xEVs in an immersive testing environment regarding its perceptibility through naturalistic driving noise and its conveyed quality impression – this ensures ecological validity while experimental control is preserved (so-called Path #2 testing according to Carbon [8]). Therefore, 3D recordings of eleven different electrified vehicles in four different driving scenarios were evaluated by a sample of sixty-five participants in a sophisticated static acoustic simulator. Instead of assessing single value responses, the methodological evaluation procedure followed the *Repeated Evaluation Technique* (RET) developed by Carbon and colleagues [37–39].

4. Method and experiment

4.1. Participants

The required sample size ($N \geq 55$) was calculated in *a priori* power analysis using G*Power [40] for multiple linear regressions, assuming a medium effect size $f = 0.15$, the error probability of $\alpha = 0.05$ and aiming at a statistical power ($1\text{-}\beta$) of 0.80. Participants were recruited and invited via e-mail in the company-internal specialist department for acoustics and vibration as well as in departments for other technical, research-related fields, but also non-technical divisions. There were no restrictions regarding participation in the study except normal hearing ability, which had to be confirmed preliminary to the experimental testing. The study was conducted according to the principles expressed in the Declaration of Helsinki and according to the ethical principles of the German Psychological Society (DGPs) and the Association of German Professional Psychologists (BDP). Participants were informed about their right to withdraw themselves and their data from the study without consequences and without stating reasons. Written informed consent was then given by each participant prior to the experimental testing. Details and rationale of the study were discussed with every participant on the completion of the experiment. The general study design (psychophysiological testing) was given ethical approval by the ethics committee of the University of Bamberg.

4.2. Material and customer-relevant use case scenarios

The driving noises of eleven different xEVs—nine battery electric vehicles (BEVs) and two hybrid electric vehicles (HEVs; operated in electric driving mode only) – were recorded with the 3D ambisonic microphone Ambeo VR Mic from Sennheiser (four channels, first order ambisonic) on a test track of the BMW Group following a standardized measurement protocol. A 3D ambisonic audio format was chosen over binaural format, as to achieve a highly immersive acoustical scene in the sophisticated experimental environment of the used simulator. To achieve a broad frame of reference of available xEV models on the market, we included test vehicles across the whole price segment from different manufacturers. Additionally, to a scenario with full acceleration like in the study of Swart and Bekker [36], further driving scenarios were included: slow acceleration (0.5 m/s^2), comfort acceleration (2.5 m/s^2), and shear/recuperation (rolling out from 100 km/h, i.e., 27.7 m/s, until stop). This was done to follow the so-called *scenario-based testing idea* by Jakesch et al. [41] to maximize the external validity of testing. These scenarios reflect situations with various de- and acceleration rates that represent the rich experience bandwidth of customers in real life. The obtained 3D recordings of the eleven vehicles in the four use case scenarios were then rendered to a suitable format for the highly sophisticated acoustic simulator. Utilizing this experimental environment, we were able to present the acoustic stimuli in a highly ecologically valid environment via wave field synthesis while targeting a significant amount of experimental control (see Carbon [8]).

4.3. Apparatus and naturalistic evaluation context

To generate a high degree of ecological validity for the e-powertrain noise evaluations, we aimed for an immersive test environment simulating real-world experience most adequately. Utilizing a highly sophisticated static acoustic simulator built out of a complete vehicle (BMW 5 series belonging to the executive car segment), including physical door opening, full functioning cockpit and complete interior equipment, we were able to provide highly realistic context information. To acoustically emulate a naturalistic driving scenario, our stimuli measurements included general driving noise from typical automotive NVH sources. Therefore, the acoustic scene consisted of different road-, tire-, wind- and powertrain-related NVH sources, which all contribute to the overall SPL to a varying extent, depending on the respective driving situation [4,6]. Utilizing the physical principle of wave field synthesis combined with a six-layer 3D audio system in the simulator, sound recordings from the test track measurements were realistically reproduced in the experimental environment. This technical and experimental setup allowed us to virtually switch between different xEV models without any physical change of test vehicles or the need to reseat the participants. Additionally, it gave us the freedom to randomize the order of trials easily and quickly.

Employing this sophisticated acoustic playback in a physical, real car allowed us to address other modalities which are typically accompanied when experiencing a car's soundscape. For instance, haptic information was provided as participants were seated on the driver's seat, accessing the vehicle's cockpit, including a real steering wheel and pedal set. Additionally, visual information was provided via a speed-accurate video projection of an artificial landscape onto the window surfaces and a speed indicator, referencing the respective speed and acceleration rate. Furthermore, contextual information about the relevant use case scenario before each test block was provided to each participant by the experimenter's instructions.

4.4. Test block design

The four recorded driving scenarios were represented by four different test blocks. In consultation with a team of specialists from the department of powertrain acoustics, the stimuli for each test block were selected from the eleven xEV-recordings. The selection criteria were a balanced subset representing the whole bandwidth of xEV models in all segments available on the market and the actual measurement quality to ensure interference-free playback of the stimuli. Resulting from the selection process, the use case scenarios for slow acceleration (SA), comfort acceleration (CA), and shear/recuperation (SR) each consisted of subsets of seven stimuli and the full acceleration (FA) scenario of a subset of six stimuli. The test blocks then were aligned to the order of a storyline of the slow acceleration (SA) followed by comfort and full acceleration (CA and FA) and finally, the shear/recuperation (SR) scenario. By presenting the stimuli of each test block in three randomized sets, participants were urged to deal with the noise examples more thoroughly as they evaluated them repeatedly [38] – this so-called *Repeated Evaluation Technique* (RET) enforces people to elaborate the material, which leads to more ecological valid testing. Additionally, this means that we gain multiple data points from the same person about the same acoustic event which effectively helps to reduce test errors. With the given repetition pattern, each test block consists of 21 stimuli (three repetitions of the seven stimuli in each subset), 18 stimuli (three repetitions of the six stimuli in the subset) in FA, respectively. The playback of the stimuli in each test block followed a randomized order. For better comprehension, Table 1 shows a sequence of stimulus presentations in the slow acceleration (SA) scenario, which exemplifies the procedure in the other use case scenarios as well. Depending on the underlying performance parameters of the specific xEV, each sound sample was presented for 11–25 s. Especially in FA, the examples were shorter as the full performance of the vehicle was retrieved. In the scenario for SR, no time limitation was given as all files were played until the recorded test vehicle came to a complete stop.

4.5. Procedure

The study on e-powertrain noise evaluation was conducted in a single testing session of 45–60 min per participant. Participants were tested individually. At the premises of the test environment, participants gave written consent (see section *4.1 Participants*) to volunteering in the study. After a brief introduction to the study's context, the participants received general information about the simulator, but remained naïve to the specific aim of the study and of the presented xEV noise examples and specifics about the repetition of playbacks. The data was obtained via a pre-programmed questionnaire on a tablet equipped with a survey tool. After the introduction by the study lead and assessing some demographic information of the participant, both test person and experimenter sat down in the simulator – the test person on the driver seat, the experimenter on the passenger seat. There was no interference of the experimenter within each test block unless there were task-relevant questions from the participant's side.

Table 1
An exemplifying order of a stimulus sequence for the slow acceleration (SA) scenario is depicted for better comprehension. In this exemplified order sequence for SA there were seven different stimuli, each representing a different vehicle recording (indicated by the code V_x, alphabetical enumeration from A to G). All seven stimuli were presented in each of the three presentation sets in randomized order. In total, the test block, therefore, consisted of 21 stimuli.

Set 1		Set 2		Set 3	
Presentation Position	Vehicle Recording	Presentation Position	Vehicle Recording	Presentation Position	Vehicle Recording
1	V_C	8	V_E	15	V_D
2	V_E	9	V_D	16	V_A
3	V_B	10	V_F	17	V_F
4	V_A	11	V_A	18	V_B
5	V_F	12	V_B	19	V_G
6	V_D	13	V_G	20	V_C
7	V_G	14	V_C	21	V_E

The stimuli were evaluated on two different dimensions: 1) *Perceived Emergence* and 2) *Overall Quality Impression*. For the first dimension, *Perceived Emergence* of the e-powertrain noise, we were interested in finding out to which extent the e-powertrain noise sticks out of the overall soundscape. This was done by using a scale for subjective evaluations established among the acoustics experts at BMW Group. Participants were instructed to "rate how strongly they perceive that the target signal (typical e-powertrain noise) breaks through the acoustical carpet" via a five-point Likert scale (1 = *inaudible*, 2 = *quiet*, 3 = *discreet*, 4 = *present* and 5 = *dominant*). The second dimension *Overall Quality Impression* aimed at assessing the overall quality impression conveyed by the specific acoustic scene considering the perceived e-powertrain noise. We again employed a five-point Likert scale, this time with the following labels: 1 = *high-quality*, 2 = *rather high-quality*, 3 = *neutral*, 4 = *rather low-quality*, and 5 = *low-quality*, and asked the participants to "rate the overall quality impression conveyed by the holistic acoustic scene considering both, general driving noise and e-powertrain noise".

The stimuli were presented in a randomized order of the described test block design. Participants were asked for their ratings of the xEV's e-powertrain noise after each stimulus presentation. Physical response was realized via a tablet computer placed in the central console of the simulator. In general, participants were admonished to answer the task as spontaneously and accurately as possible. Also, they were asked to consider each stimulus independently rather than to rank the examples amongst each other. Immediately after the ratings were submitted, the next stimulus was presented automatically. The experimenter only interfered during the testing if the participant mentioned difficulties in understanding the task. In between test blocks, the participants were given a short listening break. Then the experimenter introduced the subsequent use case scenario. After the last rating was obtained, each participant was asked to provide qualitative feedback about problems with the study procedure, any peculiarities they might have noticed and what they consider indicators for high or rather low quality regarding acoustic characteristics of e-powertrain noise.

5. Results

In the following section, the results of the study are presented. The obtained results were analyzed by using the statistical software R 4.0.3 [42]. After addressing descriptive measures and the data distribution of the ratings, analyses of the relation between the rating dimensions of perceived emergence and perceived quality and their relation to demographic variables and further study parameters are displayed. Finally, an analysis of the qualitative feedback from the participants is presented and set into context.

5.1. Descriptive measures

A total sample size of N = 65 participants, of which 48 participants were male (17 female, 0 diverse), 30 participants were from the specialized acoustics and vibrations department (35 of other departments), 37 participants stated their job was related to topics of acoustics and vibrations. With the achieved sample size, the effective test power was 86.7%. The age groups are approximately normally distributed consisting of 6% of the participants being younger than 23 years (n = 4), 28% between 24 and 30 years (n = 18), 28% between 31 and 38 years (n = 18), 23% between 39 and 47 years (n = 15), 14% between 48 and 55 years (n = 9) and 1% being 56 years and older (n = 1).

5.2. Data distribution

The ratings for the perceived emergence and perceived quality of each participant were gathered in the four different use case scenarios for each vehicle. Each stimulus was presented thrice in three consecutive, randomized repetition sets. The mean value for each vehicle in each repetition set was then computed. Fig. 1 shows the rating distribution and mean values (white dots) of the perceived emergence of e-powertrain noise for each vehicle (each indicated by a different color) in each scenario and repetition set.

The employed violin plots give an impression on which distribution the mean values were based on. Some stimuli were

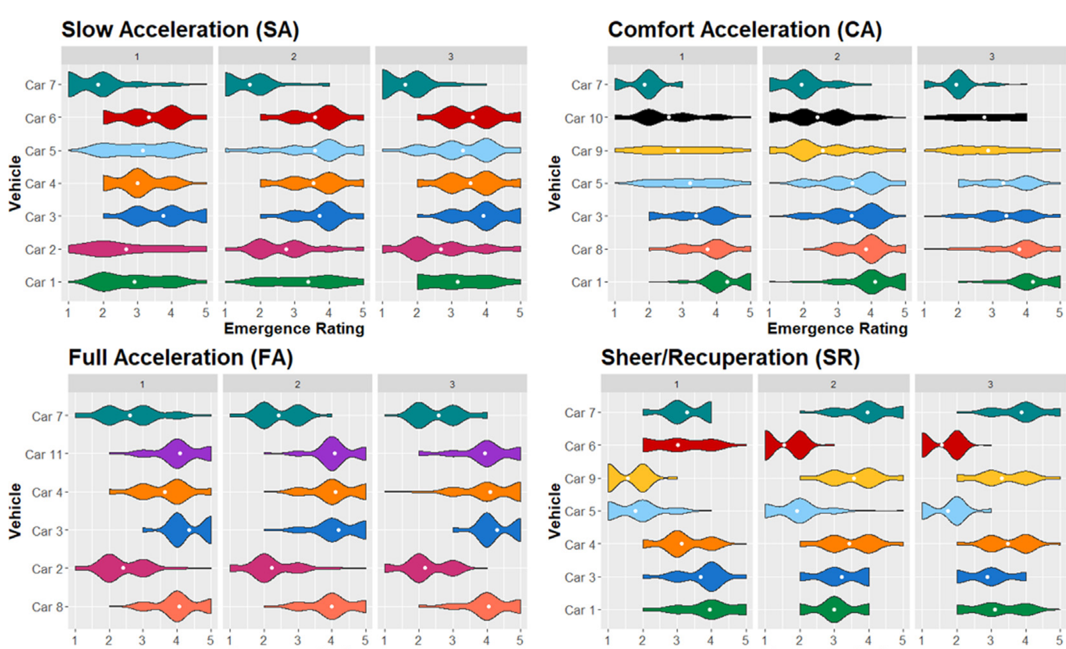

Fig. 1. Rating distribution of perceived emergence in each test block and each presentation set: The emergence rating axis is scaled as follows: 1 = *unhearable*, 2 = *quiet*, 3 = *discreet*, 4 = *present*, 5 = *dominant*; Columns *1*, *2* and *3* represent the corresponding presentation number (repetition) of each stimulus.

collectively perceived as either louder (e.g., the graphs for *Car 3* in FA) or quieter (e.g., the graphs for *Car 7* in CA). Nevertheless, a preliminary view on the data already reveals that the e-powertrain noises could not be assigned to a distinct area on the spectrum universally. One and the same sound example seems to be perceived quite differently amongst the participants since some ratings spread over several rating points. Some stimuli did not show a general trend (e.g., the graphs of *Car 9* in CA or the graphs of *Car 5* in SA).

The rating distribution (mean represented by a white dot) for the dimension for perceived quality of each vehicle (each indicated by a different color) shows an even wider span overall, indicating an even higher divergence of the participants' perception regarding the qualitative impression e-powertrain noise examples transmits (see Fig. 2). This shows, complex aesthetic evaluation is even more interindividual, and the personally perceived quality of one and the same product can differ tremendously from one person to another. There are only a few exceptions where the violin graphs do not span over the full 5-point-scaled spectrum, e.g., the graphs of the *Car 6* in SA.

As we gathered multiple measuring points with the stimulus repetition pattern in each test block, we tested whether the repetition itself affected the ratings. Therefore, we fitted a linear mixed model with the repetition set as a fixed factor and the participant-variable as a random effect using the *lmer*-function [43]. With the given test power, we were not able to detect any significant effects, neither for perceived emergence (b = 0.02, t(5200) = 1.13, p = 0.26) nor for perceived quality (b = −0.01, t(5199) = -0.86, p = 0.39). The rating patterns do not suggest a general increase of the perceived quality like suggested by the mere exposure effect for liking by Zajonc [44]. It should be noted, though, that liking is not to be compared to perceived quality, and three repetitions might not have been as thorough enough to be qualified as a mere exposure set up [45]. However, such low-frequency presentation effects of mere exposure were rarely documented (e.g., Jakesch and Carbon [46]).

5.3. Relation between emergence and quality perception

For the measures of perceived emergence and perceived quality, we revealed a significant negative correlation of τ = −.32, p < 0.001 (Kendall's Tau for rank-based data) can be found, which can be considered as a moderate relation according to Cohen [47]. Therefore, according to our findings, stronger perceived emergence of e-powertrain noise goes along with lower perceived quality conveyed by the acoustic scene. In Table 2 the correlations between the subjective measures are shown for each use case scenario, all of them being negative. As the correlations vary in the four test blocks, the perceived emergence and the perceived quality seem to be use case scenario dependent. According to the coefficient interpretations after Cohen [47], we find moderate negative correlations between perceived emergence and perceived quality in case of slow and comfort acceleration (τ = −.34, p < 0.001 and τ = −.30, p < 0.001), a small negative correlation in full acceleration (τ = −.18, p < 0.001), and a strong moderate negative correlation in the use case of shear and recuperation (τ = −.46, p < 0.001).

5.4. Relation of perception ratings and demographic variables

For most assessed demographic variables, only non-substantial relations, if even significant, were found (see Table 3). If a partici-

Table 2
Relation of perceived emergence and quality of e-powertrain noise in the four use case scenarios: Interpretation of correlation coefficients according to Cohen [47] as follows: $r \geq .10$ as a small correlation, $r \geq .30$ as a moderate correlation and $r \geq .50$ as a strong correlation. ***=p < 0.001.

Perceived Emergence per Use Case Scenario	Perceived Quality	
	r	p
Slow Acceleration (SA)	−.34	< 0.001***
Comfort Acceleration (CA)	−.30	< 0.001***
Full Acceleration (FA)	−.18	< 0.001***
Shear/Recuperation (SR)	−.46	< 0.001***

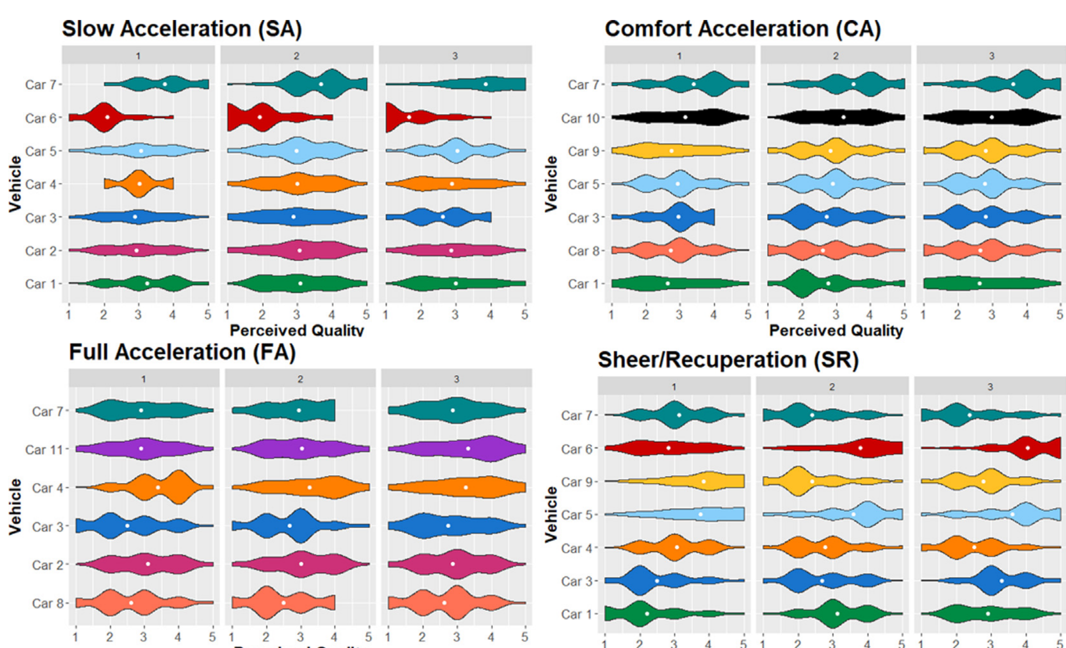

Fig. 2. Rating distribution of perceived quality in each test block and each presentation set: The emergence rating axis is scaled as follows: 1 = *low-quality*, 2 = *rather low-quality*, 3 = *neutral*, 4 = *rather high-quality*, 5 = *high-quality*; Columns *1*, *2* and 3 represent the corresponding presentation number (repetition) of each stimulus.

Table 3
Influence of demographic variables on perception ratings: Interpretation of correlation coefficients according to Cohen [47] as follows: $r \geq .10$ as a small correlation, $r \geq .30$ as a moderate correlation and $r \geq .50$ as a strong correlation. *n.s.* = not significant. **= $p < 0.01$. *** = $p < 0.001$. The coding for the different variables goes as follows: for the gender variable: 0 = *female* and 1 = *male*; for the age variable: 1 = *23 years and younger*, 2 = *24 to 30 years*, 3 = *31 to 38 years*, 4 = *39 to 47 years*, 5 = *48 to 55 years*, 6 = *56 years and older*; for the department variable: 1 = *acoustics/vibrations specialist department*, 0 = *other*; for the professional context variable: 0 = *no*, 1 = *yes*; for the variables hearing self-report and hearing report from others: 1 = *very bad*, 2 = *rather bad*, 3 = *normal*, 4 = *rather good*, 5 = *very good*.

Demographic Variable	Perceived Emergence		Perceived Quality	
	r	*p*	*r*	*p*
Gender	-.01	0.32 *n.s.*	-.04	< 0.01**
Age	.02	0.18 *n.s.*	-.04	< 0.001***
Department	.05	< 0.001***	-.14	< 0.001***
Professional context acoustics	.06	< 0.001***	-.13	< 0.001***
Hearing self-report	.04	< 0.001***	-.06	< 0.001***
Hearing report from others	.04	< 0.01**	-.02	0.19*n.s.*

pant confirmed to be either in the acoustics and vibrations department and/or to occupy oneself with such topics in their professional context, they are considered as an expert in our sample. For these variables, *professional context,* and *department,* we found significant small negative correlations in regards of perceived quality ($\tau = -.13$, $p < 0.001$ and $\tau = -.14$, $p < 0.001$). With the *lmer*-function [43] we fitted a linear mixed model with the expert status as fixed factor and the participants as random effects. It shows a significant negative effect of the affiliation to the expert group on the perceived quality ($b = -0.32$, $t(63) = -3.84$, $p < 0.001$), suggesting that experts give lower quality ratings compared to laypersons and therefore can be considered as stricter in their assessment.

5.5. Analysis of the qualitative feedback

After completing the listening tasks, we asked the participants for qualitative feedback on their personal experience in the study. In a follow-up questionnaire, the participants were asked for their remarks on noticeable peculiarities in the study and encouraged to comment on any problems or difficulties they might have had in handling the experimental task. The stated feedback was semantically analyzed, categorized into the dimensions *disturbing factors*, *experiment*, *rating*, *design aspects*, *immersion* and *other* and is summarized in Table 4. Overall, there were no fundamental problems reported, but $N = 50$ participants reported their personal experience in the study.

The feedback gives insight into the related topic and gives indications for future research. Overall, most participants were comforting during fulfilling the experimental task – accordingly, no severe problems with the study task were reported. Difficulties mostly regard the chosen study design, intentionally denying reference points for participants to anchor their assessment. The stated uncertainties reflect the somewhat novel and unfamiliar sound character of xEVs. Sporadically addressed remarks, such as statements in the categories of *immersion* and *other,* can be disregarded as they are not reflecting systematic issues with the study.

The third question referred to what participants perceived as high and low quality regarding the e-powertrain noise. Data of $N = 56$ participants were categorized into feedback regarding the e-powertrain noise's *composition*, *comparison* with other objects, *motion impression* or *emotional impact* and are shown in Table 5.

Table 4
Qualitative feedback of participants on their personal experience in the study: The statements from the qualitative feedback questionnaire were semantically analyzed, categorized into the respective feedback categories on the left, and summarized. The *N* represents the number of mentions in the corresponding category. Feedback statements were summarized. Pertinent quotes were translated from German by the authors and are denoted by quotation marks.

Feedback Category	*N*	Remarks
Disturbing Factors	31	Wind and tire noise were suspected of having affected the assessment possibly. Differently perceived acceleration rates felt hard to compare. Comparison between different car segments was not possible. Difficulties distinguishing general driving noise from e-powertrain noise – especially in the beginning of testing. Participants noticed partial masking of the e-powertrain noise by environmental noise such as wind and tire noise.
Experiment	26	Wish for the settling-in phase to gain reference points for rating. Process of "learning while listening" and sorting out if one likes e-powertrain noise or not after a while. Difficulties "perceiving the right noise". Examples were suspected to be repeatedly presented. It was noticed that sound enhancement or scenarios like idle or constant speed were not included. Number of examples was appropriate. Longer evaluation time was wished for ($n = 1$). "Many audio samples in a row" stated as non-problematic ($n = 1$).
Rating	24	Difficulties with rating scale and labels: reported to have felt not intuitive or "mixed up". Uncertainties whether to wish for acoustic operational feedback from the e-powertrain or not. Difficulties of assessing the acoustic event due to its dynamic, transient, and situational character were stated to be leading to indecisiveness about expectations regarding e-powertrain noise. Stimuli were closer to one another or farther apart than expected. The "total acoustic package" was evaluated holistically and "intuitively compared to familiar ICE noise".
Design Aspects	7	Different acoustic expectations according to vehicle engine performance mentioned as a relevant factor. Sound harmony matching the respective driving mode mentioned as a relevant factor.
Immersion	7	Lack of acceleration feedback ($n = 1$). Visual driving simulation perceived as blurred ($n = 1$). Velocity indicator found to be distracting ($n = 1$). First two scenarios were perceived as "unexpectedly loud" ($n = 1$). Video projection and scenery differed in every example. Rear view mirror did not have a picture/visual projection ($n = 1$).
Other	1	Question if a synthetic "gear switch" will be integrated ($n = 1$).

It should be noted that the stated feedback gives an insight into how interindividual the participants' preferences were regarding the soundscape configurations and that the statements need to be seen as individual indications. Causal conclusions for the exact e-powertrain configuration cannot be derived. For the *motion impression* feedback, additionally commented was that different noise characteristics and loudness levels in the different driving scenarios with varying load and acceleration ratios were to be expected and therefore accepted or at times even wished-for as operational feedback.

Table 5
Qualitative feedback on perceived quality of e-powertrain noise: The statements from the qualitative feedback questionnaire were semantically analyzed, summarized, and categorized into the respective feedback categories on the left. Feedback statements were summarized. Pertinent quotes were translated from German by the authors and are denoted by quotation marks.

Feedback Category	Quality Association	Feedback Statements
Composition	High Quality Association	"silent drive". "less noisy" and "less dominant" acoustic environment. E-powertrain noise "blending in with the surrounding environmental noise". E-powertrain "distinctively perceptible from other noise sources". More present as a kind of operational "feedback". As "vibrant", "rich" and "complex" described sounds. A "harmonic composition" of high and low frequencies. "deep frequencies", "bass" and "deep frequency proportions". "high-frequency noise". "linear rising sound". Driving scenario as relevant factor to favored kind of feedback.
	Low Quality Association	Lack of operational feedback. "very high tones are disturbing". "narrow bands and high frequencies". "too dominant bass". "prominent frequency shifts". Linear rising noise stated as negative. Negatively perceived tonal and high-frequency acoustic events described as "whining", "howling", "humming", "whirring", "buzzing", "squeaking", "whistling" or "peeping" were mentioned and partially described as even "disturbing". Some mentioned a "modulated howling" or "whining" and defined it as a "disturbing" or irregular, grinding noise". In SR some examples were perceived as having a "downwards sound" and in contrast to the acceleration scenarios described as "sad vs. happy".
Comparison	High Quality Association	Associations of low frequencies with "power", as "powerful" or an "almost real engine sound". A "futuristic tone color" and "floating" vehicles.
	Low Quality Association	Public transport associations of trains (e.g., "S-Bahn" or "Tram"). A "drowning" e-powertrain. Sounding like the e-powertrain being "tortured". "a rocket close to its impact". Association of "turbines". E-powertrain noise reminding of "games" being "too electric". Comparison to a "barrel organ". For the SR scenario: an "unpleasant richness of sound" as if it was "too high of a load" for the vehicle.
Motion Impression	High Quality Association	E-powertrain noise should "suit the load case". Expected and as "feedback of the load request" perceived noise is acceptable. A "soundscape developing according to speed". A "quiet starting noise".
	Low Quality Association	"downward sounds" and "modulating amplitudes" with increasing acceleration.
Emotional Impact	High Quality Association	"non-audible or low tones are more pleasing". "a rich sound (low to high frequencies) sounds more appealing" and is perceived as of "high quality".
	Low Quality Association	"disturbing". "unpleasant". "bad associations".

6. Discussion

According to the quantitative results and qualitative feedback in this study, the chosen acoustic simulator is suitable to evaluate e-powertrain noise in an ecologically valid environment while maintaining a great amount of experimental control. The used immersive cues for the visual, haptic and auditive context information were found to be helpful by the participants to better put themselves into the relevant use case scenario. Moreover, we were able to show that there is a moderate negative correlation between the intensity of the perceived e-powertrain noise and the overall quality conveyed by it (Kendall's Tau for rank-based data: τ = –.32, p < 0.001). This aligns with the model by Stylidis and colleagues [23], that the sound quality, a subset of technical perceived quality contributes to the overall perceived product quality (the value-based perceived quality in the model) and corroborates that NVH attributes, such as e-powertrain noise, play a relevant role in terms of ultimate overall customer satisfaction.

The often positively emphasized quietness of xEVs is, on the other hand, at times criticized for lacking operational feedback for the driver [9] or even as a loss of subjectively conveyed dynamics and vehicle character [2]. Our results support that customers wish for operational feedback according to the given acceleration scenario and, in the case of full load request, also accept and expect acoustic feedback. Blickensdorff and colleagues [9] defined the most important goals in terms of interior noise design in giving operational feedback, emotional staging, and brand sound design. Further studies need to investigate how to combine these three entities to create a pleasing interior soundscape for xEVs and how guidelines for this design task look like.

However, we would also like to elaborate on the limitations of our study. As we investigated an entirely novel vehicle sound profile, the physical environment of the chosen simulator might have been somewhat outdated. The utilized acoustic simulator built out of a former BMW 5 series, at times also available as a plug-in hybrid vehicle, does not necessarily resemble the design specifics of very recent, highly innovative electric vehicles. Generally, it should be noted that most electric cars on today's market are still based on conventional car models, so this critical point might mainly be relevant for highly innovative xEV concepts. Still, such a misfitting of visual and acoustic characteristics might bias the experience of the soundscape. Future studies could update the interior or use virtual reality instead.

Another aspect coming up short in the chosen environment is the driver interaction. An action, like e.g., pressing the pedal to accelerate the vehicle, is accompanied by certain expectations regarding the acoustic feedback. Interaction in the test environment could create a link between the participant's action and their expectation regarding the operational feedback and could therefore emulate even more realistic use case scenarios. Including more contextual cues will assist immersion and, thus, a more complete multisensory experience, while maintaining reproducible experimental conditions. To provide experimental settings, which are also economically feasible, further studies should investigate how much immersion is really needed for gaining an optimum of ecological validity.

Also, further investigations using an alternative set of semantic labels when testing perceived emergence should be considered. As assumed beforehand and further approved by qualitative feedback from participants in the study, the here employed semantic labels (*unhearable*, *quiet*, *discreet*, *present*, *dominant*) are mixing up different dimensions of perception which renders suboptimal for valid testing.

Furthermore, we would like to mention the different length of some stimuli due to the inherent nature of utilized measurements from different test vehicles with different performance parameters. Especially the stimuli in the shear/recuperation scenario varied strongly in their length (13–47 s) due to the different recuperation rates of the xEVs. As derived from our data, there seems to be a very heterogeneous bag of opinions concerning how strongly the e-powertrain noise is perceived, as well as what kind of noise is perceived as of high quality in the recuperation scenario.

Since participants were left in the dark regarding the given product class and further specifications of the presented vehicle, the subjectively perceived quality is especially dependent on each individual's frame of reference and expectation horizon. It is therefore not possible to derive any insights in terms of specific product placement. The finding of the slightly stricter quality assessment of the expert group in our study might be a good example of this individual reference frame, as experts have broader experience with the palette of available products. Moreover, it is their job requirement to compare in-house products critically against the products of competitors. Due to its novelty character, the dynamics in evaluating e-powertrain noise and the expectations to it are difficult to assess. The more experience people gain, the more elaborative their assessment of the presented examples will be. The qualitative feedback from our participants supports this, as they often stated to have felt very indecisive about their rating or to be surprised by how close, or in some cases, how wide apart, the acoustic examples were.

The frequently noted difficulties in differentiating the e-powertrain noise from driving noise or singling it out of the sound carpet in the given evaluation tasks support the axiom of Gestalt psychology [24]. With the inclusion of the naturalistic driving noise, which partially masked the e-powertrain noise, we aimed to obtain holistic scenario evaluations, which therefore are applicable to the external world and real-life customer scenarios.

Finally, it needs to be highlighted that the qualitative data obtained about the associations of high or low perceived quality represent individual preferences. The presented comments therefore can be seen as explorative reference points of what people might associate with different e-powertrain noise conveying a certain level of product quality. Nevertheless, further investigations on the semantics and associations expressed by the soundscapes of xEVs need to be made.

7. Conclusion

The findings of this study support e-powertrain noise to be a customer-relevant attribute, as it conveys information about the product that contributes to the product's overall quality impression of individuals. As this study shows, the subjective perception of an xEVs' soundscape can differ greatly among different individuals, even if the presented stimulus is the same. These differences are even more prominent in more complex perceptual domains such as perceived quality. Our data also shows that despite the overall positively emphasized the quiet sound character of xEVs, customers accept or at times even expect and wish for operational feedback in certain situations as e.g., in the full acceleration scenario. Further investigation on the exact configuration of the e-powertrain noise in terms of its profile is needed to understand what kind represents a favorable combination of characteristic NVH phenomena, leading to a pleasing, customer-oriented in-cabin ambience soundscape for xEVs.

CRediT authorship contribution statement

Mara Münder: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Claus-Christian Carbon:** Conceptualization, Methodology, Validation, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mrs. Mara Münder, MSc is currently enrolled in the PhD-program of the BMW Group and Bamberg Graduate School of Affective and Cognitive Sciences (BaGrACS). Professor Claus-Christian Carbon, PhD is founder and board chairman of the Bamberg Graduate School of Affective and Cognitive Sciences (BaGrACS) and the Research Group EPAEG (Ergonomics, Psychological Aesthetics, Gestalt). He acts as PhD supervisor for Mara Münder but receives no money for this duty from BMW – he is fully independent regarding his supervision and advises given to Mara Münder.

Acknowledgments

The authors would like to thank the measurement engineers at the BMW test track and Tobias Jaensch for the technical support and realization of the study in the acoustic simulator. Moreover, we would like to thank the NVH specialists for e-powertrain noise of the department for fruitful discussions. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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