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A method for Perceptual Assessment of Automotive Audio Systems and Cabin Acoustics

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ABSTRACT

This paper reports the design and implementation of a method to perceptually assess the acoustical properties of a car cabin and the subsequent sound reproduction properties of automotive audio systems. Here, we combine Spatial Decomposition Method and Rapid Sensory Analysis techniques. The former allows instant comparisons between auralized measured Vehicle Impulse Responses (VIR) over loudspeakers, avoiding headphone-related shortcomings, while rapid sensory analysis overcomes time-consuming product profiling and language-specific problems, commonly found in the evaluation of audio material. The proposed method is described in terms of capturing, analyzing and reproducing the sound field. A brief overview of the experimental procedure is presented as well as preliminary results of a pilot experiment.

1. INTRODUCTION

Over the last decades the automotive industry has been focusing in identifying and improving the major factors that influence the sensory experience of the vehicles. As a consequence, the study of sound quality in automotive audio systems has been brought into the limelight.

The highly complex acoustical environment of a car cabin minimizes the effectiveness of standard objective measures, lacking robustness, repeatability and perceptual relevance. This has lead to the use of human auditory perception as a the major instrument in car audio evaluation, both during development as well as aftermarket benchmark processes [1–9]. Aiming towards high-quality reproduction, car audio manufacturers normally employ listening tests to identify and characterize the physical alterations of this type of sound fields. These alterations relate to electroacoustic properties of the transducers, their placement and performance, cabin's properties, as well as signal processing algorithms (i.e. upmixing & sound tuning).

Assessing sound is ultimately a process that requires merging its *perceptual* and *physical* characteristics in a common space. In acoustics, understanding the perceptual effects of the physical properties of a space would enable a better understanding of its acoustical qualities and stipulate perceptually relevant ways to compensate for the subsequent degradation.

The physical characterization of sound fields has mainly focused in performance and typical sound reproduction spaces. Later, several objective metrics have been established and standardized [10, 11]. Numerous studies have also investigated the perceptual constructs of these acoustical fields, aiming to identify the corresponding sensory descriptors and quantify the human sensations. A recent in-depth review of these studies [12] has revealed that these perceptual constructs could be domain specific, as the physical characteristics of the room, complexity of the stimuli, and listener's expectations may affect our perceptual and cognitive processes.

The experimental procedure employed in perceptual evaluation of audio material is normally driven by the contextual factors, given limitations and application

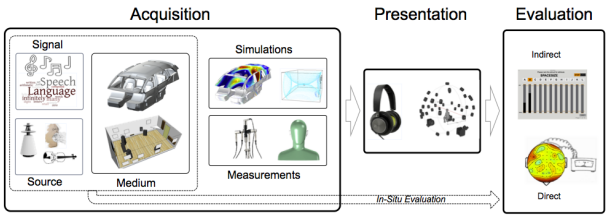


Fig. 1: Basic principles undertaken in perceptual audio evaluation.

of research, which typically translates into a domain-specific standardization. Most experimental methods and recommendations are typically based on a three-step process: *acquisition*, *presentation*, and the *evaluation* of a stimuli set. A graphical summary is given in Fig.1. Based on these principles, several standardization schemes have been applied in audio evaluation in several domains. For example a recommendation for experimental procedures for small degradations in audio signals [13] and good practices for evaluation of audio in network transmission protocols [14]. Such a standard is not available for car audio evaluation [3].

Several experimental procedures have been exploited in automotive audio evaluation, which can be classified into two categories: (1) *in-situ* (2) Laboratory-based evaluation. It is logical to assume that *in-situ* evaluation provides the highest *ecological validity* possible. It is therefore not a surprise that such evaluations formed the industry standard. However, exposing assessors in such settings introduces strong biases caused by non-acoustical factors (i.e. size, price, brand). Later, Shively [6] proposed a form of a blind *in-situ* evaluation. Nonetheless, *in-situ* methods inherently include long test-to-test periods between the different *Device Under Test* (DUT) which is known to affect perception thus, its judgment. It is therefore likely that the experimental results are influenced in an uncontrolled manner; i.e. effects of the assessor's auditory memory, mood, and expectation [15].

These limitations were the driving force into developing laboratory-based evaluations methodologies. The most commonly used method incorporates *dummy-head* measurements at the driver's position which are then used to synthesize the binaural field and present the auralization over headphones. A process known as *Binaural Car Scanning* (BCS) [4, 16]. These approaches form a valuable tool in car audio as they overcome practical complications of *in-situ* evaluations, in addition to allowing rapid comparisons between car cabins or audio systems - something not possible previously.

It is however realized that headphones reproduction based on dummy-head measurements result to lack of *externalization* - known as *in-the-head* perception of sound - not accurate timbral reproduction at low frequencies, as well as lack of 'whole-body' vibrations - a sensation known to affect listener preferences in binaural reproduction [17, 18]. In practice, such methods are also time consuming as obtaining *Impulse Responses* (IRs) with a dummy-head requires hundreds of measurements per system.

1.1. Motivation

Perceptual evaluation of acoustic properties in rooms and consequently in car cabins, is highly influenced by the methodology employed, which is typically limited to the specific context factors. A trade-off between the requirements of high *ecological validity* and direct, single-dimensional *variable control* is apparent, imposing application-specific approaches.

In car cabins, the complex sound field requires stimuli acquisition in the form of measurements, or *in-situ* evaluation under real conditions. When assessing *in-situ* a number of non-auditory features and expectations introduce more restrictions. Yet, the benefit of assessing several automotive audio systems and cars in a comparative method seems superior to the uncontrolled auditory memory [19] assumptions during *in-situ* testing.

In this paper, we present an alternative approach towards capturing, presenting, and evaluating automotive sound. The method is based on *Spatial Decomposition Method* (SDM) [20], that has successfully been applied for perceptual evaluation and spatial analysis in both concert halls [21] and critical listening environments i.e. studios [22]. The SDM is a spatial analysis and synthesis scheme, where the obtained IRs can be analyzed parametrically as a pressure and direction of arrival values. Therefore the sound field is decomposed in terms of direction and time of arrival.

Capturing and analyzing the sound field using SDM in cars may lead to two major advantages over the previously discussed methods. First, the spatio-temporal analysis provided by the method may enable better understanding of the behavior of the sound field in the cabin. The method includes additional physical quantities and visualization capabilities, that could be used when the spatial attributes are in question. Second, it allows a variety of reproduction protocols (e.g.*Vector Based Ampli-*

tude Panning (VBAP), *High Order Ambisonics* (HOA)). Thus, a loudspeaker reproduction system could be employed, overcoming the issues of headphone-based playback, such as the lack of 'whole-body' vibration and not externalized sound.

2. EXPERIMENTAL METHOD

This section describes the proposed audio evaluation methodology for capturing, analyzing, synthesizing, and presenting automotive sound. Here, the reproduction of the auralized stimuli is conducted over loudspeakers in an anechoic chamber and the assessment follows *Sensory Analysis* (SA) procedures, as the optimal combination for this study. It is noted that the presentation and evaluation method could be altered based on the research objectives and the related practical implications. For example presentation on headphones is still possible, as well as following standardized audio evaluation methods as Basic Audio Quality [13], while the spatio-temporal analysis of the measured field will still be available to the researcher.

2.1. Acquisition - In-situ Car Measurements

In order to obtain the acoustic characteristics of a sound reproduction system in a car cabin, *in-situ* recordings of a four-door sedan were performed. The car was equipped with 17 band-limited transducers (5 tweeters, 7 mid-range transducers, 4 woofers, 1 subwoofer) and a custom multichannel amplifier. The audio system included an experimental tuning by a tonmeister, thus the feed to the individual transducers was post-processed (i.e compensation delays, equalization) to represent a typical production car, equipped with a high-end system.

An open spherical microphone array (G.R.A.S VI-50) comprising of two coincidental microphones on each axis, separated by 25mm, was positioned at the driver's seat, at the average seating position [23]. The microphone probe was aligned to match the position of a dummy-head seating in the car - the center point of the head and ears' height. The distance between the microphone array and the headrest was set to 15cm.

The IRs were measured in a way that the (electrical) input to the amplifier was captured by the electrical output of the microphones in the cabin, including any signal processing in the signal path of the audio system. These measurements will be referred to as *Vehicle Impulse Responses* (VIRs).

The VIRs were measured for each transducer, using a 5s logarithmic sine-sweep (1Hz-24kHz) method [24] at 192kHz using an RME UCX multichannel sound interface. The measurement system was calibrated with 5s pink-noise to produce 82dB C-weighted sound pressure level in the car cabin as measured at the forward facing microphone of the array, with system's default settings. The electrical output of the measurement system was kept constant for all drivers. The car measurements were conducted in a temperature and noise regulated garage at Bang & Olufsen's premises.

2.2. Spatial Analysis and Synthesis of VIRs

The spatial analysis and synthesis of the car's sound field was implemented based on SDM [20]. SDM divides the sound field into spatially discrete elements of a preset analysis window. SDM assumes a wide-band source i.e. a typical full-range loudspeaker, therefore it is recommended to use as short window as possible [20, 25]. In this experiment the captured VIRs were band-limited, due to the type/size of each transducer in the cabin. Hence it was possible to implement a custom window-length (L) settings based on the properties of the transducers - at least three periods of the shortest wavelength in the frequency band analyzed. This allows a more accurate spatial decomposition of the sound field - an important advantage when analyzing such complex sound fields as in car cabins. The analysis was performed on the captured VIRs with no modifications as described in 2.1.

In a recent study [25], the spatial analysis and synthesis of a car audio system using SDM is described in detail including experiments conducted to evaluate the undertaken methodology. In that report, experiments have shown that a post-equalization of the loudspeaker spectra should be employed when SDM is used in car cabins. The high echo density found in a car cabin may introduce abrupt changes of the calculated *Direction Of Arrival* (DOA). In consequence excess wide-band transients may be introduced in the synthesized *Impulse Response* (IR). A detailed of the spatial analysis and synthesis procedures followed in the current paper, is given in [25].

2.3. Reproduction Protocol

SDM provides a spatial analysis and signal encoding for a given set of VIRs allowing auralization of the sound field using a given Spatial Decoding and Reproduction scheme over loudspeakers, or Binaural Synthesis based on anechoic *Head-Related Transfer Function* (HRTF). In this paper, the synthesis of the SDM-encoded spatial IRs was implemented using the *Nearest Neighbor* (NN)

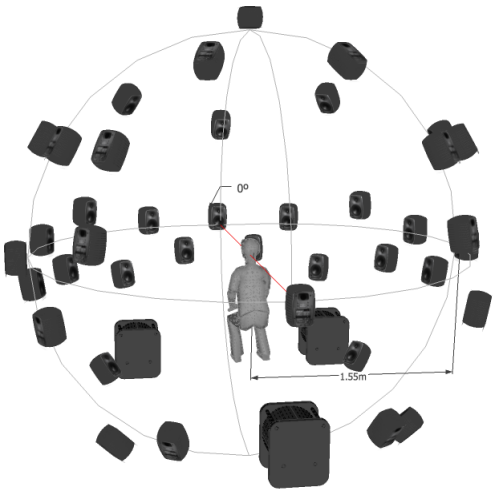


Fig. 2: The loudspeaker are placed in a spherical orientation (r=1.55m). Loudspeakers are mirrored-placed anticlockwise in (AZ,EL): 0,0; 11,-10; 22,0; 32.5,-15; 45,5; 55,-10; 65,0; 75,-10; 90,0; 120,-10; 135,10; 0,30; 40,40; 90,30; 115,30; 135,30; 150,55; 0,90; 55,-40; 120,-45; 150,-35.

loudspeaker, similar to [22]. Although reproduction with SDM was first employed using VBAP [26], the synthesis of the soundfield using direct-feeds of SDM-samples to the nearest-loudspeakers with respect to the direction parameters of that sample was found to provide more natural sound without reducing the perceived *brightness* [27].

2.4. Reproduction Setup

In order to provide as close spatial reproduction as possible when new type of environments is to be auralized with SDM, accurate spatial analysis of the soundfield should be performed to identify the placement of the loudspeakers in the reproduction system. As shown previously [25] the directional energy responses of a single mid-range loudspeaker in a car-cabin includes reflections within very short time intervals i.e. in the case of a Front Right Mid-range that was 0.5 ms as measured at the (left) driver position. Thus, individual *Vehicle Impulse Response* (VIR) analysis was employed to ensure that the direct sound as well as reflections from the cabin's surfaces are preserved, in the best possible way, during the reproduction phase. A systematic approach was followed, using objective and perceptual evaluations. The spatio-temporal energy distribution in time intervals [28] of each measured VIR was combined with the corresponding weighted energy error estimation. This error term, is inherently caused by fitting SDM-samples to the NN loudspeakers instead of their absolute position given in the analysis. The perceptual assessment focused on three perceptual constructs, *spectral fidelity*, *temporal integrity* and *accuracy of spatial representation* for two auralization sets: a full car audio system, and single transducers. Attention was also given to the electroacoustic properties of the loudspeakers and the spatial acuity of the human hearing system, ensuring high level of detail in the frontal plane, whilst maintaining the perceptual qualities from all directions. During the design of the loudspeaker setup, it was noted that a second layer of loudspeakers at lower elevation (-10 °) in the frontal plane (-70°- +70°) was necessary. In fact, the direct sound will only arrive from lower elevations in a car cabin due to the lack of transducers at ear-height at this plane.

For the final auralizations a 40.3 loudspeaker system was specified (see Fig. 2). The setup comprises of 40 full-range speakers and 3 subwoofers. Each loudspeaker was calibrated with 5s pink-noise *in-situ* at 80.5 $\pm$0.5 dBC_{RMS} measured with a single omni-directional microphone at the listening position. The magnitude response of the loudspeakers was also confirmed to lie primarily within $\pm$1.5dB, including a low-frequency compensation ($<$180Hz) at the listening position.

2.5. Reproduction Signal Flow

The loudspeakers are driven by a laptop computer over a MADI interface (RME MADIXT). Three D/A converters, 2xRME M16 and 1 x ADI-8 are used to distribute the signals to the individual loudspeakers in the reproduction setup, at 48kHz sample rate. This setup was also used during the calibration procedure including an additional A/D converter (RME Micstacy). The system is self-compensating for internal AD-DA conversion, and has been verified to deliver sample-accurate response at all channels, an overall delay of 18 samples. The ADI-8 introduces an additional 10 sample delay due to MADI-ADAT conversion. Moreover, the inherent inconsistencies in the physical placement of the loudspeakers introduce different time of arrivals at the listening position. Thus, the acoustic delay between each loudspeaker and a microphone at the listening position was measured and the reproduction channels were individually compensated.

2.6. Reproduction Environment

When assessing spatial audio over loudspeakers, it is necessary to decrease the acoustic influence of the reproduction room, on the reproduced soundfield that we intend to evaluate [29], as it is known to be perceptible

by listeners [30, 31]. This is normally achieved by ensuring that the reproduction room is characterized by a lower reverberation time compared to the room that is being reproduced via the system. Due to the nature of the sound-field in a car-cabin and the very short reverberation time [32], the setup was installed in the anechoic chamber (B5-104) located at Aalborg University. The chamber is designed and constructed to host simulation setups with human occupancy, and it is treated with absorption wedges that are 0.4m long. Its free inner dimensions are 5.0 x 4.5 x 4.0m. The chamber meets the requirements for anechoic performance [33] down to 200Hz. The physical setup was covered with absorption material to eliminate any reflections from the structural installation.

3. PERCEPTUAL EVALUATION METHODS

Due to the complex and multidimensional properties of audio, most audio perceptual evaluation methodologies require a set of verbal descriptors known as *perceptual attributes*, so that human assessors are able to epitomize and appropriately quantify their sensations for the given set of stimuli. The experimenter may employ an *attribute elicitation* methodology, or define a set of attributes that has been known to form the perceptual space for the given stimuli set [29].

Sensory Analysis (SA) methodologies found in food and wine industry [34, 35] have been instrumental in decoding complex perceptual constructs and hedonic responses of human assessors. Such methodologies hold key importance in multidimensional products such as audio. Over the decade several approaches have been successfully applied in concert halls [21, 36], spatial audio reproduction through loudspeakers [37–41] and headphones [42], hearing aids [43], and active noise cancellation [44].

Descriptive Analysis (DA) is known to be the most sophisticated tool [34] in SA allowing the experimenter to extract information normally hidden behind hedonic and affective judgments, or linguistic inaccuracies leading to a more detailed investigation. It is however known that conventional descriptive SA require extensive training per product, as well as multiple sessions (5-6) per assessor [34, 45]. The time restrictions within the automotive environment and the requirement of product-specific training of DA may not suit well automotive audio. In a need for less time-demanding methods, *rapid sensory profiling* techniques have been proposed recently (see [15] for review).

The most closely related rapid method to conventional profiling is *Flash Profile* (FP) [15,46]. FP highly emphasises on rapidity aiming to provide a perceptual 'snapshot' of the product's properties as perceived by the assessors and a relative ranking of each product [15, 45]. The biggest advantage over other non-verbal based methods is that it is based on quantitative description, allowing statistical analysis to create a common space i.e. using *Generalized Procrustes Analysis*. The FP only requires 4-5 expert assessors who complete the process within a single 1-3 hours session.

In this study the experimental procedure follows FP recommendations to assesses its applicability in this context, as at the authors knowledge, FP has never been used in audio evaluation before.

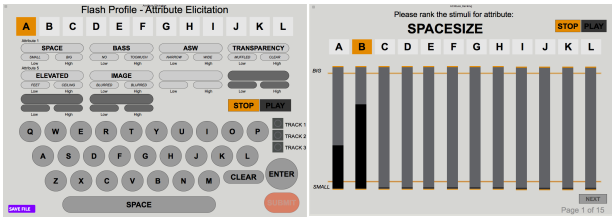
4. PILOT EXPERIMENT

The sections above described a novel method for perceptual assessment of automotive audio. For reasons of completion, a brief description of a pilot study using the proposed method is included. The data presented here is a part of a formal evaluation that is currently under investigation, and should be interpreted with care. The study's objective was to quantify the perceived differences imposed by altering the acoustics of a car's cabin. In the example below the perceptual effect of the *Front windows* and the effect of the *Equalization* (EQ) (tuning) by an expert tonmeister is in question. The conditions used in the assessment are summarized in table 1. A short description of the experimental procedure is given below.

4.1. Materials & Apparatus

For this experiment three *in-situ* sets of car measurements were used. Each set included VIRs of all seventeen individually measured transducers, as described in section 2.1. Each VIR was analyzed using SDM. Music material (*Armin van Buuren feat. Ana Criado - I'll Listen*) was then convolved separately with the corresponding 40.3-channel SDM responses. The playback was based on multichannel 24bit PCM sampled at 48kHz.

The assessor was given a touch-screen wireless tablet (iPad 2) controlling MAX 7 via MIRA on a Macbook Pro. A custom patch controlled the multichannel audio files and data collection. The interface of the patch was similar to the one found in MUSHRA [47]. The reproduction room, setup and signal chain and calibration measurements were identical to the aforementioned settings in section 2. The assessor was seated on a predetermined location located at center of the spherical array. The height was altered to match the acoustic center



(a) Verbal Elicitation GUI (b) Attribute Ranking GUI

Fig. 3: User interface during the two phases of the experiment. Letter buttons included different acoustical conditions of the car cabin. The interface was touch controlled on a tablet.

of the loudspeakers at 0° elevation using leveling laser. The whole experiment was conducted in complete dark conditions, and the assessor was not aware of the room, loudspeaker setup and the content of the stimuli as suggested by [15, p99].

No	Condition
1	No Equalization (inc. delays)
2	Normal Condition - Tuned
3	Front Windows Open - Tuned

Table 1: Summary of conditions used in the experiment.

4.2. Experimental Procedure

The experiment comprised of two parts: 1) the *elicitation* of attributes and 2) the *ranking* of the elicited attributes. The assessor was first introduced to the FP methodology, focusing on the correct elicitation of non-hedonic, singular and rank-able descriptors that do not exhibit redundancy [29, 34].

4.3. Experimental Design - Elicitation

The assessor was asked to provide a non-limited number of verbal descriptors that capture the perceptual characteristics of the whole stimuli set presented. The stimuli were available on a single screen and the assessor was able to play any stimulus at any point, using all tracks provided[1]. The order of presentation was randomized for each assessor. The procedure was self-controlled and self-paced; the GUI is shown in Fig.3(a).

4.4. Experimental Design - Ranking

During the ranking phase the assessor was asked to rank the stimuli based on the perceived intensity differences of the given attribute. Each given perceptual attribute formed a block of three trials (one trial per program material). The order of presentation of the stimuli as well as the program material was randomized on each trial. The graphical interface is show in Fig.3(b).

[1]This paper only reports one track and three conditions for reasons of simplicity.

4.5. Results

The results of this pilot investigation are given below for a single assessor. The assessor was an expert sound engineer with experience >10 years in developing, evaluating and tuning car audio systems as well as SA methodologies. The assessor is considered as a product expert.

The initial results presented here show that the system is capable of eliciting the expected responses based on the changes in the sound field. Figure 4 shows that although the 'image focus' is preserved between *Normal Conditions* and *Windows Open*, the perceived 'Width' differs marginally. The perceived 'transparency' seems to decrease when the windows are open, compared to the other conditions presented here. Moreover, perceived 'Distance' shows no difference between the two EQ settings whilst it was ranked higher for *Windows Open*, as one would expect due to lack of side reflections.

These results indicate that the assessor perceived the physical changes in an expected way, which come in close agreement with previous elicitation studies in automotive audio [1] and spatial audio reproduction [12]. It should be noted that the data presented here is an illustrative set and should not be used to conclude findings due to the limited contextual factors. An in-depth analysis will be presented in future work.

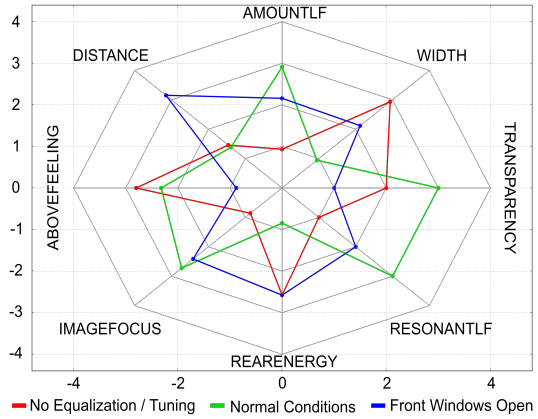


Fig. 4: Spider plot depicting the responses given by the subject. The values are standardized (M=0). Note that the attributes given here were elicited using a larger set of stimuli.

5. DISCUSSION

This paper described a method to capture, analyze, re-

produce and evaluate sound originating from car cabins. The proposed method maintains the benefits of perceptual assessment in the laboratory via auralization similar to BCS. Thus, the method allows rapid and comparative assessment of different sound fields in the lab, in double-blind settings, overcoming issues related to non-auditory feedback (i.e. brand) during *in-situ* evaluation, and the need for a car prototype systems for long periods during development phases. The system also allows a choice of reproduction schemes (i.e. Binaural Synthesis, Wave-Field Synthesis, VBAP). In this study a loudspeaker-based reproduction was followed in an anechoic chamber, ensuring a natural externalization of the reproduced sound field. In addition it includes a full-range reproduction system (23Hz-20kHz) to satisfy low frequency response similar to the car cabin and natural 'whole-body' vibrations, with minimal effects of the reproduction room. Finally, following the proposed method the required time for stimuli acquisition is significantly reduced as capturing the VIRs require less time compared to BCS.

Christensen et al. [4] suggested that providing real driving simulations i.e. Steering Wheel, may enhance the realism of the evaluation. In this study, we aim to remove any visual influence which is known to affect perception, thus, the behavioral outcome (p96 in [15]), an issue raised when performing car audio evaluation.

In the paper Sensory Analysis is also discussed as a tool for audio evaluation. Flash Profile aims for rapid profiling of a product within a single session whilst the assessor can use individual vocabulary. The downside is that the experimenter cannot argue on the semantic meaning of the descriptors. However performing statistical analysis in multiple assessors the perceptual constructs could be decomposed and provide better understanding of the soundfield when merged with the physical metrics within the stimuli.

One should note that the SDM provides a faithful and plausible acoustical representation, however, as any spatial reproduction method to date, it has certain limitations. As it was shown recently [25], a post-equalization of the analyzed response is needed when this is applied to cars due to high echo density. Moreover, the complex geometry of a car cabin and the extreme acoustical conditions may violate the basic assumptions of SDM of plane waves, thus one should not expect that the reproduced sound field is an exact replica of the recorded. The current SDM assumes single reflection per analysis window, which may not be always the case in a car cabin. Nevertheless, both objective and perceptual results suggest that SDM preserves the perceptual differences between the stimuli set in the experiment - a vital requirement for perceptual assessment. The advantages of the method rely on the flexible reproduction scheme, the fast acquisition of VIR compared to BCS, as well as analysis and visualization capabilities of the spatial properties of the VIRs.

Further work on this topic aims to understand the perceptual effects of acoustical properties (i.e. reverberation) in everyday listening spaces, such domestic rooms and car-cabins. The above methodology is currently followed in assessing car-cabins in detail, aiming to identify the perceptual constructs originating from acoustical alterations in the sound field in question. Moreover a database of multiple car cabins has been established to be perceptually evaluated, aiming to provide insights in the perceptual characterization between different-sized or type of car cabins, as well as sound systems within similar cabins, and the effect of human occupancy [4]. The proposed methodology will also be applied in small room acoustics aiming to perceptually assess a variety of acoustical settings in standard listening rooms and to better understand the interaction between the acoustical properties of the reproduction room that are inherently imposed on the reproduced sound field.

The experimental methodology proposed here, is an example of an application in car audio evaluation. However, the method could be applied in many domains. Since SDM is a parametric approach, certain applications could be realized by the using the suggested system, such as development of tuning tool for a car audio system in the lab, as well as sound and system design testing algorithms, without the need of a prototype car.

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