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Perceptual aspects of reproduced sound in car cabin acoustics

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An experiment was conducted to determine the perceptual effects of car cabin acoustics on the reproduced sound field. In-car measurements were conducted whilst the cabin's interior was physically modified. The captured sound fields were recreated in the laboratory using a three-dimensional loudspeaker array. A panel of expert assessors followed a rapid sensory analysis protocol, the flash profile, to perceptually characterize and evaluate 12 acoustical conditions of the car cabin using individually elicited attributes. A multivariate analysis revealed the panel's consensus and the identified perceptual constructs. Six perceptual constructs characterize the differences between the acoustical conditions of the cabin, related to bass, ambience, transparency, width and envelopment, brightness, and image focus. The current results indicate the importance of several acoustical properties of a car's interior on the perceived sound qualities. Moreover, they signify the capacity of the applied methodology in assessing spectral and spatial properties of automotive environments in laboratory settings using a time-efficient and flexible protocol. © *2017 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4976816]

[MV] Pages: 1459–1469

I. INTRODUCTION

Automotive environments are steadily becoming popular listening spaces. Aiming toward a high quality reproduction, in-car audio systems have reformed from an adequate monophonic reproduction, at first, to today's multichannel loudspeaker systems capable of delivering some of the most advanced audio schemes available.[1] In acoustical terms, automotive audio systems exhibit unique and domain-specific challenges that increase the complexity and the development requirements.[2,3] The unconventional and adverse acoustical properties of the car cabins[3,4] are unequivocally the dominant challenges when developing such audio systems.

The physical characteristics of such a sound field[5,6] and their effects on human perception[2,3] are not well understood. That is, current objective metrics fail to reliably characterize the physical properties of these sound fields in a robust and perceptually relevant way.[7–11] As a consequence, automotive audio manufacturers rely heavily on the human perception as the instrument to characterize, evaluate, and optimize the sound quality of car audio systems. Typically, an iterative process is followed where alterations on the audio system are perceptually evaluated, targeting the most pleasing aural experience.[2,12–14] A number of studies investigated human perception in automotive audio by primarily focusing on comparative evaluations of (1) within audio system comparisons, such as preference on equalization,[15,16] digital signal processing (DSP) algorithms,[13] and perceptual codecs,[2] as well as (2) in-between audio system comparisons and market benchmarking purposes.[14,17–19]

To the authors' best knowledge, there is no published literature on the perceptual effects of the acoustic transmission medium, the car cabin itself. Understanding the salient factors affected by the cabin's acoustics could aid the development of perceptually relevant models and metrics for assessing automotive audio. Moreover, it would depict the underlying relationship between physical and perceptual qualities of the car audio systems, enabling a more efficient optimization of the in-car aural experience.

In a recent study,[20] it was shown that current perceptual evaluation protocols within automotive audio may not be able to faithfully capture the characteristics of cabin acoustics and a new assessment methodology was proposed. Here, this methodology is applied in the context of car cabin acoustics, where several physical modifications of a cabin's interior have been perceptually evaluated by expert assessors.

The aims of this study are: (1) to investigate the influence of acoustical properties of car cabins on the perceived qualities of the reproduced sound, (2) to identify the underlying relationships between physical and perceptual properties within car cabins, and (3) to establish and further validate the applied experimental framework[20] followed for assessing the acoustical properties of sound fields within automotive audio.

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In Sec. II, the rationale behind the study is discussed and the experimental methodology is described. The data analysis is then presented in Sec. III, followed by the results and conclusions in Secs. IV and V, respectively.

II. METHOD

The experimental methods followed in this study include novel approaches in the acquisition and presentation of the captured sound fields, as well as in the evaluation processes. This approach enabled the perceptual assessment of car cabin acoustics in laboratory settings. It further allowed human assessors to identify individually elicited perceptual attributes, which characterized both the spectral and the spatial properties of the sound fields under investigation; a serious limitation of previous studies.[13,16,17,20]

Spatial decomposition method (SDM)[21] is employed for recording and reproducing the sound fields to human assessors. As an alternative technique to binaural rendering,[3,16] this method eliminates several shortcomings related to binaural audio schemes[22] such as the lack of *externalization* and the subsequent difficulty in assessing spatial acoustics.[13] SDM has been successfully applied in the assessment of perceptual qualities of concert halls,[23,24] as well as in evaluating small-sized spaces, e.g., studio control rooms.[25] The applicability of SDM in automotive environments has been recently investigated and a recommendation was proposed.[26]

Identifying the perceptual constructs underlying the cabin's physical properties would require a protocol where novel and uncommon aural experiences could be characterized and evaluated. This could be accomplished with descriptive *sensory analysis* (SA)[27] techniques. However, common SA procedures are time-consuming, laborious, and expensive, as they require product- and panel-specific training over multiple sessions.[27,28] This is a major limitation in the time-restricted automotive industry. This paper applies a *rapid* SA method, i.e., the *flash profile* (FP),[29] and assesses its applicability within the automotive environment.

Several practical limitations exist in automotive audio assessment that FP seem to overcome. FP limits the required evaluation time by omitting the familiarization, the panel training, and the consensus vocabulary phases. Moreover, FP does not require product-specific training, compared to the traditional descriptive SA methods. This allows the use of assessors with general sensory expertise, requiring only 4–5 expert assessors for a statistically stable outcome.[29,30] Nevertheless, FP is the closest rapid method to conventional descriptive SA,[29] and it allows the quantitative description of stimuli by statistically merging the quantitative and qualitative data in a common factorial space.

A. Experimental design

The experimental design followed FP[31,32] principles, adapted to assess audio material.[20] FP includes two experimental phases in a single session. First, each assessor is required to develop its own set of perceptual descriptors during an attribute *elicitation* phase. Later, an attribute *ranking* phase is conducted where assessors comparatively quantify all stimuli simultaneously, by means of ranks, for each of the elicited attributes.

Two *independent variables* (IVs) were included in the experiment. The acoustical *condition* (12 levels) combined with *program* (3 levels), resulting to a total of 36 stimuli. The ranking scores of each stimulus on the elicited attributes formed the quantitative *dependent variables* (DVs).

B. Assessors

Four expert assessors participated in the experiment as volunteers. The assessors had 10–15 years of experience (mean = 12, standard deviation (sd) = ±2.15) in critical listening, acoustical development, and sound tuning of premium automotive audio systems. As part of their profession, assessors have been trained to use their senses in critically evaluating the qualities of audio signals. They have all participated in numerous listening experiments and they were familiar with common SA procedures. All four assessors were male, aged 29–45 years old (mean = 38). Their hearing sensitivity was confirmed to lie above 20 dB hearing level (HL) between 125 and 8000 Hz by standard hearing threshold procedures.[33]

C. Materials and apparatus

In a series of previous studies, the apparatus has been described in detail including in-car acquisition of *impulse responses* (IRs), spatial analysis and synthesis of a car audio system using SDM,[26] as well as the design and implementation of the experimental setup and the methodology[20] followed here. A brief description of these topics is given in Secs. II C 1–II C 4.

1. In situ car measurements

In order to capture the acoustical characteristics of the car cabin, *in situ* measurements were performed in a sedan-type car (Audi A8 Typ.4E, Germany), equipped with a premium audio system. The system was comprised of 17 independent transducers driven by an automotive digital amplifier. The system is shown in Fig. 1.

Individual spatial IRs were captured for each transducer of the system by a vector intensity probe (G.R.A.S. 50VI-1, Denmark), placed at the average seating position of the driver.[34] The measurements were conducted in a temperature and noise regulated garage ($V = 206\,\mathrm{m}^3$, reverberation time $(\mathrm{RT}_{30}) < 0.2\,\mathrm{s}$ at 125–8000 Hz). These measurements are further referred to as *vehicle impulse responses* (VIRs).

The signal path was set in such a way that the acquired VIRs included DSP processing (sound tuning), designed by a tonmeister. That included spectral and level balancing of the system, delays, and individual tuning of the transducers magnitude responses in order to achieve a perceptually pleasing reproduction. This signal flow ensured that the experimental apparatus represented the performance of a typical premium automotive audio system.

2. Acoustical conditions

The interior of the car cabin was systematically modified so that a representative range of possible acoustical

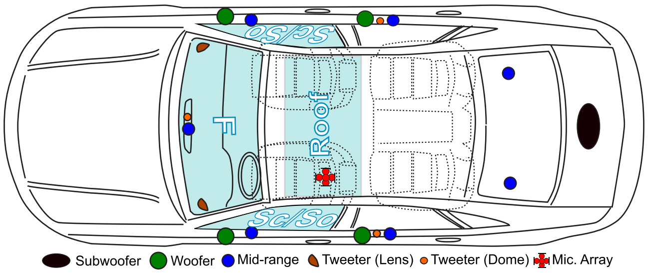

FIG. 1. (Color online) In-car audio system used in the measurements. The position of the microphone array is shown at the driver's position. Shaded areas, labeled as *Sc*/*So*/*F*/*Roof*, indicate the surfaces modified during the measurements (see descriptions in Table I).

fields was captured. The main compartments of the car's interior were altered in such a way that the first arriving reflections of the cabin's sound field were affected, as well as the later reflections, and combinations of both. The acoustical measurements obtained formed the experimental conditions as summarized in Table I.

Seen from the driver's seat perspective, the major reflection points in this car have been identified on the glass surfaces of the cabin, namely, the side door windows and the windshield.[20,26] In order to alter these reflections, 0.04 m thick Basotect foam (BASF, Germany)[35] was used to fully cover the glass surfaces for condition *Sc*, as well as condition *F* and their combinations, conditions *FSc*, *FSo*, *AbsF*, and *AbsSc*.

Although common room acoustics metrics, such as RT, cannot be generalized in car cabins,[5] it is common to observe decay times of 80 ms at mid-frequencies from measured IRs. To investigate the effects of the decay time of a car cabin, e.g., due to human occupancy or highly absorptive interior, another acoustical condition was included. A collection of absorptive materials was added to the cabin, including a 3.4 m × 0.04 m rolled Acoustilux, with radius of 0.35 m, placed at the rear seats, highly absorptive fibre textiles placed at the interior's floor, and four pylons of polyurethane foam sized 0.15 × 0.25 × 1.2 m on the front seats. Attention was given so that the direct acoustical paths between the sources and the receivers were not obstructed by the added materials.

TABLE I. Acoustical modifications used in the experiment. Condition *Ref* serves as the reference, representing a typical production car, equipped with premium audio system and no acoustical modifications. A dash indicates no alteration from car's reference settings.

Condition	Side windows	Windshield	Ceiling	Cabin	DSP
Ref	—	—	—	—	—
EQ1	—	—	—	—	Alternative
EQ0	—	—	—	—	Disabled
Sc	Absorptive	—	—	—	—
So	Open	—	—	—	—
F	—	Absorptive	—	—	—
FSc	Absorptive	Absorptive	—	—	—
FSo	Open	Absorptive	—	—	—
Abs	—	—	—	Absorptive	—
AbsF	—	Absorptive	—	Absorptive	—
AbsSc	Absorptive	—	—	Absorptive	—
Roof	—	—	Reflective	—	—

Recently, car manufacturers have incorporated glass roofs instead of the conventional textile upholstery. In order to accommodate the effects of such a scenario, condition *Roof* was included, where a unified glass tile (1.0 × 0.6 × 0.05 m) was attached to the ceiling of the cabin, positioned symmetrically above the front seats. During this condition, the absorptive nature of cabin's ceiling was altered to exhibit strong reflective characteristics. The topology and details of the above alterations are given in Fig. 1.

The reference condition, indicated as *Ref* (Table I), refers to the captured sound field where the car cabin and DSP processing were unmodified, as the production automotive audio system, and it is further used as the baseline. Two additional conditions were included in the experiment, where only the DSP processing of the audio system was modified; the cabin's properties were kept at the reference settings. First, an alternative DSP processing preset was included, referred to as *EQ1*, where the door-woofers output was reduced −3 dB and the balance between the front left–center–right transducers was altered, aiming to increase the spatial width[36] compared to *Ref*. In addition, a condition where the system's DSP processing was disabled altogether is referred to as *EQ0*. These two conditions were integrated in the experiment to assess the perceptual effects of sound tuning, compared to the physical alterations of the cabin's interior. Moreover, they could form the experimental anchors, as the physical alterations imposed on the system are known to elicit certain perceptual differences to experienced sound designers. In this way the validity of the method and the subsequent experimental results could be verified.

3. Reproduction system

In order to recreate the captured sound fields in the laboratory, a suitable reproduction system is required. For this study a 40.3 spherical loudspeaker array, depicted in Fig. 2, was designed. The design of the loudspeaker array was based on a spatiotemporal analysis[37] of the aforementioned VIRs (Sec. II C), including additional measurements of 20

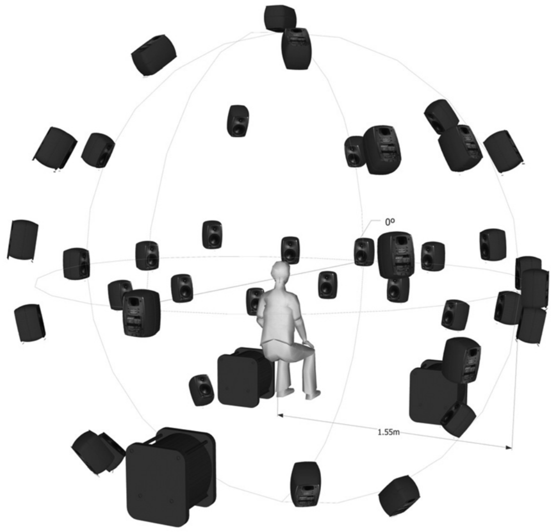

FIG. 2. Reproduction system comprising of 40 full-range loudspeakers and three subwoofers (Ref. 20).

different types of cars and audio systems.[20] This analysis was essential to ensure that both the direct sound from car's transducers, as well as the subsequent reflections, were optimally reproduced in the laboratory. To limit the influence of the experimental room to the investigated sound field, the reproduction system was installed in an anechoic chamber.[38]

4. Signals

The captured VIRs were processed with SDM.[26] The SDM is a spatial analysis and synthesis scheme where the sound field is decomposed in terms of pressure, direction and time, and encoded into a spatiotemporal domain.[37] The SDM-encoded signals are then divided into individual IRs, which are then used for synthesizing the sound field using a finite loudspeaker grid by means of convolution with audio material.

Here, three audio excerpts were chosen based on the results of two pilot studies. The excerpts used were: (1) *Armin van Buuren featuring Ana Criado—I will Listen (2012)–0:15–0:30*, (2) *Melody Gardot—She don't know (Currency of Man, 2015)—2:01–2:16*, (3) *Female Speech English (EBU SQAM, 2008)—0:00–0:15*.[39] The sound excerpts formed the three levels of program, which are further referred to as dance, jazz, and speech. These signals were loudness-matched before convolution at 15 dB$_{\text{LUFS}}$ and perceptually validated by an expert listener *in situ*. During the experiment, the reference reproduction level was set to 75 dB $_{\text{LAeq(15s)}}$ at the listening position.

D. Procedure

First, the assessors were briefed about the experimental procedure and the principles behind FP protocol. As part of their introduction, a custom MAX/MSP interface[20] was presented, and the assessors performed a training session where no sound was provided. They were then guided inside the testing facility. The experiment was conducted in dark conditions and controls were imposed so that the assessors were unable to see the experimental apparatus until they completed the experiment.

The experimental process was controlled by the assessor over a self-paced and -controlled software on a touch screen. The assessor was aware that there were no time limitations to complete the tasks. Short breaks were allowed and regularly recommended to avoid possible listening fatigue.

E. Attribute elicitation

During the attribute elicitation phase, each assessor was asked to provide as many discriminant attributes as needed, to fully capture the perceived differences between the available stimuli. Emphasis was given as to provide precise, singular, non-redundant and low-level terms, that one could rate on a scale between a *high* and a *low* intensity. It was also recommended to avoid hedonic and affective expressions relating to preference or acceptance.[27] Within the interface one could define the extreme intensity anchors of each attribute. For example, for the attribute "loudness," the assessor could define its scale anchors as "quiet" and "too loud," respectively.

During the elicitation phase all 12 conditions (Table I) were presented simultaneously on the screen, labeled as A–L, as required by FP guidelines.[29] The order of the stimuli was kept constant within each session and randomized between assessors. The software provided the option to change program whilst listening to the same condition so that perceptual differences between specific conditions could be explored over a variety of programs. Before completing the task, participants verified that their attribute list described the main perceptual differences between all 36 stimuli (3 programs × 12 conditions). At the end of the elicitation phase, an interview was conducted where the assessor provided short definitions for the elicited attributes.

F. Attribute ranking

The second phase required the assessor to comparatively rank the experimental stimuli for each of the individually elicited attributes. At this stage, the evaluation followed a block design. The number of blocks was based on the number of the attributes given by that assessor. Each attribute was evaluated in three sequential trials, one for each program level. At each trial the stimuli were randomly assigned to 12 buttons labeled as A–L. The presentation order of the program levels and blocks was randomized as required by standard audio evaluation procedures.[40]

III. DATA ANALYSIS

The collected data included 37 individually elicited attributes and their corresponding ranks for each of the presented stimuli, as shown in Fig. 3. Several multivariate techniques could be followed to analyze such a dataset, e.g., *general procrustes analysis* (GPA)[41] and *multiple factor analysis* (MFA),[42] both providing similar group-average patterns.[29] The mathematical transformations of MFA provide a number of complementary information, allowing the analysis of qualitative and quantitative data in a common latent space.[43,44]

In this study, the analysis is based on MFA, aiming to devise a common consensus space across assessors, whilst identifying the most important components, observations, and attributes.[44,45] MFA studies the relations between several predetermined groups of attributes and it could be viewed as a

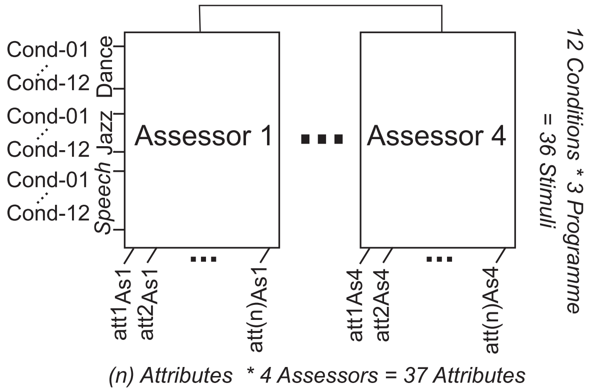

FIG. 3. Data structure used for the MFA, comprised of the observations of 4 assessors, denoted as As1-4, using a total of 37 individually elicited attributes, denoted as Att(1-n). The data include all 36 stimuli used in the experiment.

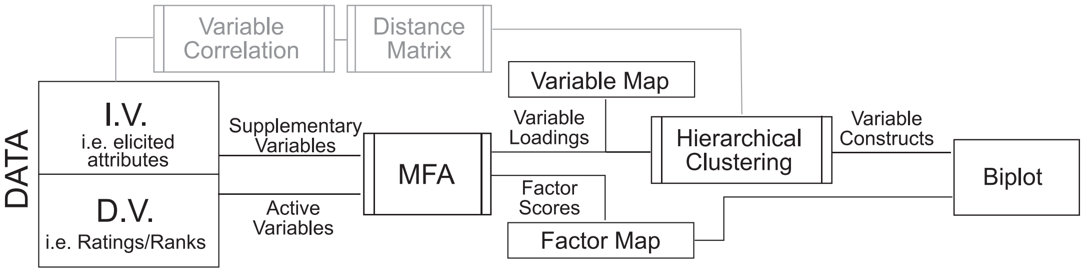

FIG. 4. Schematic representation of the data analysis. Active variables refer to the data points used for the calculation of the latent dimensions using MFA. Supplementary variables do not contribute in the calculation of the dimensions, but could be included for further statistical analysis, i.e., their correlation to the latent dimensions is visualized by projecting them into the MFA solution as vectors. The alternative clustering process followed for cross-validation of clusters hierarchy is shown in grey.

consensus principle component analysis (PCA), built on a set of equally weighted principal components. MFA performs PCA on the attributes of each assessor separately, which are then normalized[46] to balance the influence of each group on the computation of the consensus space. The PCA data are then merged into a global matrix where a final PCA is performed, estimating the consensus solution across all assessors.

The outcome of such analysis is the positioning of stimuli on a consensus space. Similarly to a PCA, the interpretation of a stimulus position is based on its calculated coordinates on each dimension, the *factor scores*, and the corresponding variables explaining these dimensions, referred to as *variable loadings*. The inter-stimuli relationships are based on the relative distances between the stimuli's coordinates on the consensus *factor map*. The rationale behind this sensory profiling could be explained by projecting the variable loadings on the consensus space, creating what is known as the *variable map*. The advantage of analyzing FP data using MFA is the ability to jointly interpret these two quantities on a common factorial space. This approach enables the researcher to identify the underlying perceptual constructs of the stimuli profiles based on the structure within the data. The statistical analyses described in this section are summarized in Fig. 4.

A. Ordination with MFA

MFA was performed on the collected observations (Fig. 3) using *FactoMineR* package.[47] To reduce any scaling effects[48] between assessors, the raw data were centered by subtracting the mean values of each column (attribute) and normalized by dividing the centered data of each column by its root-mean-square. The analysis shows that almost 54% of the variance is explained by the first two principal components, and the remaining components seem to provide little contribution to the explained variance as shown in Table II. Figure 5 shows the positions of the stimuli on the first plane, as a factor map. At this initial screening it can be seen that the stimuli are well separated in the first two common dimensions. *EQ0* and *AbsF* hold the extreme positions on dimension 1, whilst *Roof* contrasts those two conditions, on dimension 2. *Ref*, *EQ1*, and *Roof* are positioned relatively close to each other in both dimensions, as expected, due to their subtle audible differences. Moreover, it can be seen that the more absorption added in the cabin, the more negative the dimension 1 becomes for these stimuli. This can be observed by contrasting the baseline's dimension 1 coordinates (*Ref*) to the condition where absorption is added in the cabin (*Abs*). Adding absorption material on the side windows (*AbsSc*) and the windshield (*AbsF*) continues to have a negative effect on dimension 1.

TABLE II. The first five principle components of the MFA analysis based on the analysis of the normalized and centered data.

Principle component	Eigenvalue	Percent of variance	Cumulative percent variance
1	3.53	39.65	39.65
2	1.26	14.24	53.89
3	0.53	6.01	59.90
4	0.45	5.15	65.05
5	0.34	3.91	68.97

B. Influence of program and acoustical conditions

A common way to identify significant differences within the stimuli-set in the latent MFA space follows the calculation of 95% *confidence ellipses* (CEs),[49] an analogous metric to *confidence intervals*. The CEs of condition levels are depicted in Fig. 5, indicating good separation between most condition levels, as seen on the first two dimensions. These observations indicate that the panel of four expert assessors

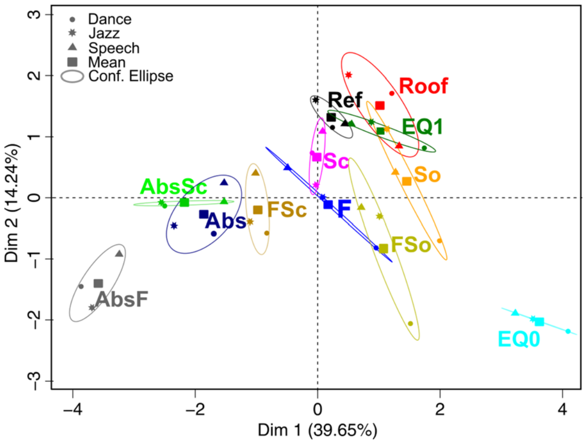

FIG. 5. (Color online) MFA consensus space depicting the coordinates of the 12 conditions included in the experiment on the first 2 principal components. The points indicate the factor scores of each of the 36 stimuli, signified by their program level and colored by the condition level (see Table I). The 95% confidence ellipses (CE) depict the significant differences between conditions.

TABLE III. The first five principle components of the MFA analysis based on the averaged data across program.

Principle component	Eigenvalue	Percent of variance	Cumulative percent variance
1	3.78	56.85	56.85
2	1.23	18.61	75.47
3	0.42	6.36	81.84
4	0.36	5.53	87.38
5	0.24	3.68	91.06

provided sensory ratings that are significantly different between different conditions.

Moreover, it is noted that most of the 36 stimuli are clustered together, in groups of three, following their corresponding condition level. No systematic bias can be seen for a specific program excerpt, or extreme values that would indicate program dependence of the acoustical conditions. This indicates that stimuli are ordered similarly even when different program excerpts were used. Further analysis verified that the program has no significant effect on the perceived differences within the various conditions ($R^2_{\mathrm{Dim1}} = 0.001$, $R^2_{\mathrm{Dim2}} = 0.04$, $p = n.s.$).[47]

C. Generalizing results—Averaging

In order to achieve a holistic understanding of the data and focus on the IV of interest, the acoustical conditions, a MFA was performed on the averaged data across program. This approach addresses the relatively low explained variance of the first two dimensions (54%) of the previous analysis by accounting for the noise within the data at lower dimensions. Moreover, since the program was found not to be a significant factor, the relative positions of the stimuli would be preserved.

The variances explained by the first five dimensions of the MFA analysis on averaged data are summarized in Table III. The first two dimensions explain 75.47% of the variance and there is minimal contribution by the remaining individual dimensions (<7%). Figure 6 depicts the factor scores based on the analysis of the averaged data. As expected, the relative positions between the conditions are very similar to the ones in Fig. 5, yet explained by notably higher variance.

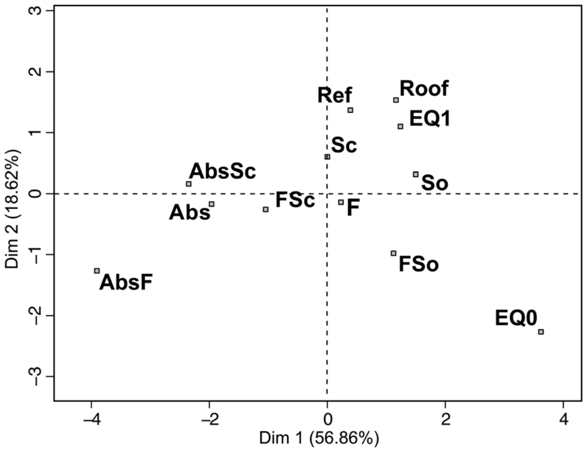

FIG. 6. The resulting factor map of the MFA analysis using averaged data across program. The map depicts the position of stimuli on the panel's consensus space.

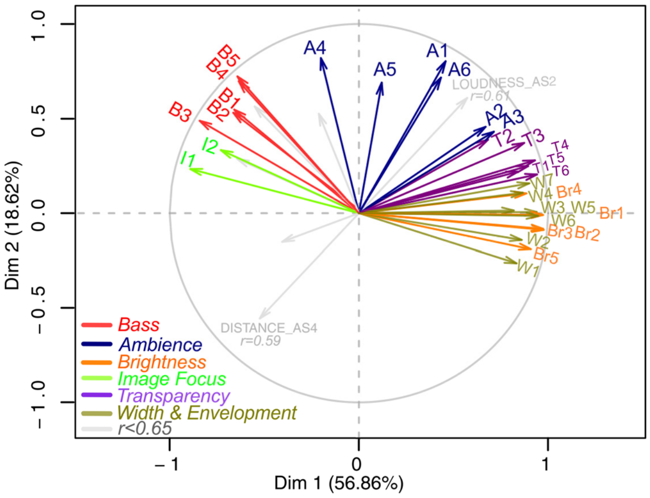

FIG. 7. (Color online) Variable map from MFA analysis if the program-averaged data, depicting the projections of the individual attributes as vectors on the first consensus plane. The length of the vector indicates the correlation to the factorial solution. The vectors' colors indicate their cluster group, as calculated in Sec. III D. The attributes' labels referred to the convention used in Fig. 8. Grey vectors indicate the excluded attributes and include the label and assessor's number.

The variable map, shown in Fig. 7, depicts the attributes of each assessor projected to the MFA plane. A high number of attributes is well represented on the first two dimensions, making the graphical interpretation a difficult task. Reducing the number of attributes would enable a better interpretation of the results. That is, classifying the assessors' own attributes into collective categories and in consequence into the common underlying perceptual constructs.

This could be done semantically, based on the homologous terms and the definitions given by assessors. However, in FP each assessor uses his/her own vocabulary, thus, an attribute given and scored by an assessor may not necessarily relate to a semantically similar attribute given by another assessor.[43] A mathematically based approach, i.e., using the geometrical and the statistical properties of the data points,[44] would reveal the true structure within the dataset. Combined with the definitions given by assessors the *internal validity* of the formed clusters could be assessed. That is, the extent on which the grouped variables measure and represent similar sensory constructs. Recently, such methods were successfully applied on individually elicited attributes of audio material, and allowed the identification of the common perceptual constructs across 31 (Ref. 28) and 23 naive assessors.[50]

D. Clustering of elicited attributes

The grouping of attributes was achieved using *agglomerative hierarchical clustering* (AHC), based on the Euclidean distances of the MFA coordinates of each attribute in conjunction with Ward's criterion.[28,51] As clustering is blind to the importance of each attribute to each dimension, thus, susceptible to noise, the attributes included in the analysis were pre-selected based on the correlation of the attribute to any the first two principal components

($r > 0.65$).[52] This noise reduction process accounts for these limitations of AHC and the clustering process provides equal hierarchical weights between the well-correlated variables only.

Two main clusters can be identified in the resulting dendrogram in Fig. 8. The first cluster is formed by two subcategories, one described by attributes related to *bass*, and one related to the spatial *image focus*.[53] The second cluster splits into four subcategories and includes attributes related to *ambience, width and envelopment, transparency*, and *brightness*. It is noted that the attributes clustered well together semantically, especially for the clusters related to *bass*, *brightness*, *image focus* even if no consensus vocabulary or panel training was included in the procedure. The attributes related to *width* and *envelopment* fall into the same cluster. This comes in agreement with previous studies,[36] where assessors used these attributes interchangeably as they both contributed to the perceptual construct of spaciousness.[54] Yet, it could also indicate that the stimuli used in the experiment failed to excite these constructs separately.

These six clusters observed here are thought to encompass the perceptual constructs underlying the stimuli-set in this investigation. Although the individual attributes may differ within a cluster, e.g., "image_AS1" has been grouped under "transparency," the clustering algorithm identified a perceptual equivalence across the grouped attributes. That is, the assessors rated similarly the stimuli for these attributes, even if they are not semantically related, a common observation in free-elicitation experiments.[43] Here, the clusters were labeled following the definitions given by the assessors during evaluation, in combination to previous studies on spatial acoustics[36,55] and sound reproduction[56] to maintain consistency across studies and illustrates the author's best understanding.

It should be noted that the input to the clustering algorithm used here included the coordinates of the attributes on all dimensions given by the MFA analysis. This allows to directly project clusters on the latent MFA space, as seen in Fig. 6. Yet, AHC might produce hierarchies for objects that are not hierarchically interrelated.[57] To validate the clustering process, an additional AHC was performed. Using the raw data, the correlation matrix of the attributes was used as the input of the AHC in the form of a distance matrix.[44] This clustering revealed similar results to the original clustering, confirming the validity of the dendrogram depicted in Fig. 8 and the perceptual constructs identified.

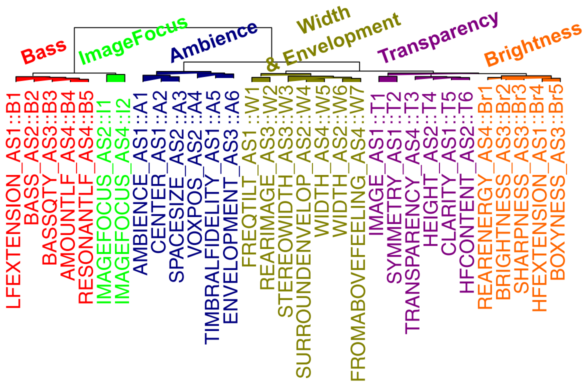

FIG. 8. (Color online) Dendrogram of the individually elicited attributes. The clustering processes were based on the MFA coordinates of the averaged dataset. The first eight dimensions were used in the clustering, based on Euclidean distances and Ward's criterion. As($1-4$) denotes the assessor's number.

IV. RESULTS

The interpretation of the data can be achieved by graphically combining the results of the statistical analysis described in Secs. III C–III D in the form of a Biplot. That is, merging the consensus factor scores of the MFA (Fig. 6) and the perceptual constructs identified by AHC. To achieve this, the MFA coordinates of the individually elicited attributes are averaged per cluster and then projected into the MFA factorial space. This process allows the efficient visualization of the results by simultaneously presenting the major quantitative and qualitative observations. Figure 9 depicts the summarized results of this paper, combining the factor scores and the identified perceptual constructs. The perceptual constructs are realized as directional vectors, providing a tangible explanation for the variance within each dimension.

As the conditions are a combination of several factors including modification of: (1) front side windows, (2) windshield, (3) roof, (4) cabin absorption, and their combinations, the best interpretation of this graph is achieved by analyzing comparatively conditions where single changes occurred.

A. Validation—Effect of equalization

First, by focusing on the conditions where only the DSP settings were modified, i.e., *EQ0, EQ1*, one could verify whether the identified factor space and the related perceptual constructs come in agreement with our expectations and current knowledge.

The DSP settings of *EQ0* included a substantial reduction at low frequencies (-15 dB) compared to the reference DSP settings (*Ref*), which explains its projection to the basis vector being directly opposite to the perceptual construct of bass, as seen in Fig. 9. This denotes that assessors identified a decreased low frequency content when listening to *EQ0*. The minor differences in the low frequencies of *EQ1* compared to *Ref* have also been perceived by the assessors at the appropriate intensity level, indicating only a slight increase of bass for *EQ1* compared to *Ref*. The close positioning of the *EQ1* and *Ref* supports that audible differences were subtle, as noted. In contrast the extreme position of *EQ0* in Fig. 9 indicates perceptually strong differences compared to the other stimuli.

Moreover, *EQ1* included slight alterations on the spatial and spectral balance of the front channels. The constructs of width and envelopment and brightness indicate slightly higher intensities of the *EQ1* compared to *Ref*, on the expense of reduced image focus. The position of *EQ0* indicates high values against these perceptual constructs on dimension 1, which follows the expected results, as the sound tuning of the automotive system is based on the optimization of such constructs.

These observations suggest that the evaluation method successfully captured the perceptual differences across stimuli, depicting the underlying perceptual factors and the relative intensities in an expected way. That is, the ability of the experimental apparatus to facilitate the perceptual

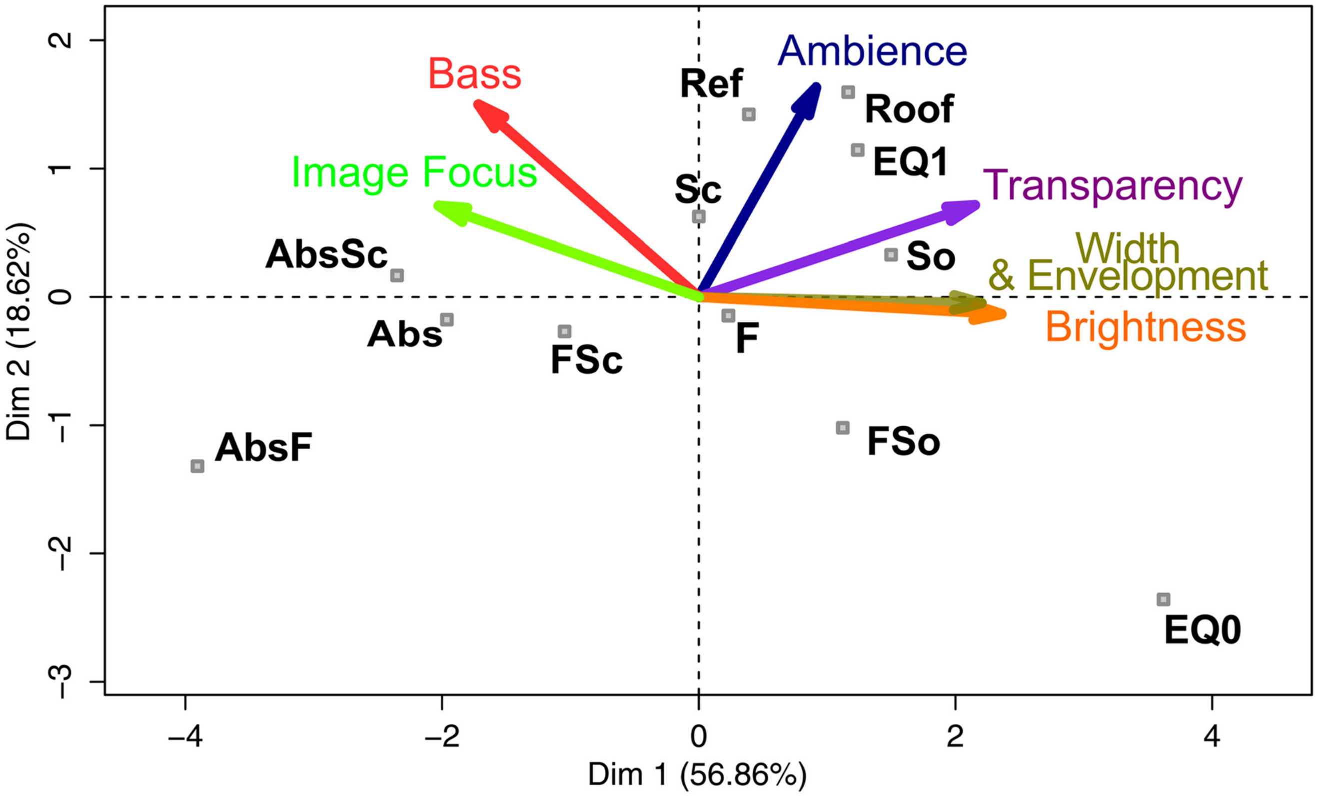

FIG. 9. (Color online) Biplot depicting the perceptual constructs and the stimuli factor scores. The identified constructs are projected in the factorial space by calculating the average coordinates of each cluster's attributes.

differences across the measured sound fields and its capacity to identify and signify these differences by employing the statistical procedures described in Sec. III.

B. Effect of roof

A glass added on the ceiling of the cabin would increase the energy coming from above the listener, especially at higher frequencies. The number of the very first arriving reflections may also increase, affecting the echo density of the field as well as the perceived interaural differences. These physical alterations have been linked to the perceptual attributes of apparent source width, envelopment, and spaciousness.[36]

Based on Fig. 9, *Roof* is closely positioned to *Ref*, indicating slight perceived differences. The main differences can be seen on dimension 1. This indicates that adding a glass to the ceiling increases the perceived width and envelopment, brightness, and transparency. Minor increase is noticed on the perceived ambience. Image focus is decreased, however, which could relate to comb filtering due to the added early reflections of the ceiling.[58] That is a spectral interference of coherent signals, which may be perceived as spectral and spatial alterations of the originally emitted signal. Interestingly, *Roof* and *EQ1* seem to hold equal positions in dimension 1, indicating their perceptual similarities.

C. Effect of absorption

Acoustic damping materials were added in the cabin, aiming to decrease the decay time of the cabin's sound field and consequently the perception of the apparent room size[36] and reverberance.[50] The position of *Abs* compared to *Ref* indicates a much less ambient field, less wide and enveloping, yet, a more focused sound image. This observation may relate to the decreased number of strong and dense reflections from multiple directions. Perceived brightness is also decreased, as expected, due to the highly absorbing materials used, at this frequency range. This spectral imbalance of the system could be also observed by the identified increased bass content.

These observations are also supported by contrasting the position of conditions *F* and *AbsF*, as well as the *Sc* and *AbsSc*; all indicating perceptual equivalence of conditions when the absorption in the cabin increases.

D. Effect of front side windows

Two conditions aimed to investigate the perceptual effects imposed by the reflections of the front side windows. In condition *So* the windows were open, so that the reflections originating from the glass surface were eliminated, and the cabin was an acoustically open cavity. In a second alteration, *Sc*, the door's glass surface was covered with absorptive material, aiming to decrease the subsequent reflected energy.

The two conditions, *So* and *Sc*, revealed dissimilar sensory profiles as seen in Fig. 9, even if the same surface was altered. When absorption was added (*Sc*), the perceived bass was highly similar as to *Ref*. In contrast with the *So* condition where the windows were open, the amount of low-frequency energy in the cabin was perceived as reduced. That is an expected result, as the absorption material used in the experiment was only affecting high frequencies; opening the windows should also affect the modal behavior of the cabin. Similarly, an increase is apparent in the perceived width and envelopment at *So*, compared to when windows were covered with absorption material as in *Sc*.

These trends can also be seen by comparing the conditions *F–FSo*, where the relative difference between the two was the front side windows state. The relative distances and projections of this pair indicate their perceptual similarities to *Ref–So*. This may indicate that the perceptual effects of opening the side window are independent of the windshield properties.

1. Side windows—Absorptive

The effect of increasing the absorption of the side windows seems to decrease the perceived ambience, and the bass content at a lower degree. No major alterations can be seen on the perceived width and envelopment and brightness. This would be an unexpected observation for room acoustics, as the side reflections are known to affect these perceptual constructs.[59,60] One could hypothesize that such results may indicate a different auditory processing scheme[61] when exposed to car's sound fields; due to the highly dense early reflections that arrive within a few milliseconds, in contrast to the distinct and sparse reflections in typical rooms.[59] Yet, it should be noted that the car audio system was equipped with acoustic lens technology[62] at the front tweeters, where the dispersion area of the high frequencies is optimized. Therefore, such reflections could be limited in this experimental setup. Thus, the expected effect on spatial width may not have been perceived in this investigation.

2. Side windows—Open

To investigate the effect of the side windows in a different way, the glass surface of the front doors was removed. Based on the positions of *Ref* and *So* in Fig. 9, it can be seen that the perceived ambience is less apparent when windows are open. The sound is also perceived slightly more wide and enveloping and brighter, whereas the image focus decreases. This condition should indeed affect the perceived ambience, as the cabin was not a closed cavity anymore. Moreover, perceived bass is affected, in agreement with previous findings of possible standing waves along that direction[26] and increased room gain in car cabins.[63] These findings are also supported by examining the factor scores of *F* and *FSo*, as their relative positions are highly similar to *Ref* and *So*.

E. Effect of windshield

The perceptual effects of adding absorptive material on the windshield, referred to as *F*, are mainly apparent on the second dimension compared to reference condition. The reduced energy coming off the large glass surface opposite the driver seems to reveal a less ambient and less transparent sound field, yet, width and envelopment and brightness are not affected.

However, comparing *Sc* and *FSc*, where the relative physical change between conditions was identical to *Ref* and *F*, perceptual effects are apparent also on dimension 1. This is an intriguing result that may indicate a strong relationship between the combined front and side reflections, on the perceived spatial properties, when the cabin is a closed cavity.

V. CONCLUSIONS

The study employed a recently proposed evaluation methodology for automotive audio to address the perceptual effects of car cabin acoustics. The experimental methodology included the SDM for the acquisition, analysis, and presentation of the sound fields to human assessors, whilst a rapid SA protocol, FP was adapted and used for audio material. The method provided individual vocabulary profiling from expert assessors, in a single experimental session of 1.5–3 h in total.

The findings indicate the importance of the acoustical properties of a car cabin on perceived sound quality. It was shown that even slight alterations in the cabin, for example, adding a reflective glass surface above the listener, have a notable impact on the perceived sound field. Moreover, the significance of reflections originating from the windshield was identified as in a previous study,[64] as well as the influence of the side windows on the perceived sound, and a relationship between the two surfaces was also apparent. The optimization of the system by means of equalization and DSP processing seems to highly alter the aural experience, supporting the relevance of the industry's current sound tuning approaches. Finally, the identified effect of added absorption, even at extremely short decay times may reflect on the proposed influence of passenger occupancy[3] on the reproduced sound in cars. One could infer relations of these results to previous investigations that sought to identify the perceptual aspects of sound in enclosures, e.g., studies in concert halls[28,50] and sound reproduction in small rooms.[59] A comprehensive literature review[36] suggested that the perceptual space characterizing performance spaces, sound reproduction in domestic rooms, and automotive audio seem to be heterogeneous. The current results support this notion. That is, similar trends could be observed but the interrelations of the perceptual constructs differ, and a direct comparison would be an inaccurate representation. As similar studies in the domain of automotive audio were not identified, the perceptual space cannot be contrasted directly to previous results. Here, specific findings were compared to related literature.

The investigation demonstrates the applicability of the FP in perceptual evaluation of automotive audio systems. Further, it allowed a statistically robust characterization of the stimuli-set based on multivariate analyses of both quantitative and qualitative data. The underlying perceptual constructs of the sound fields were identified, and projected against a data-driven factorial analysis. Two stimuli-anchors were used in the experiment, *EQ1* and *EQ0*, where their factorial position and perceptual interpretation comes in agreement with our expectations and empirical knowledge. This further validates the experimental design[20] and the subsequent data analysis.

Nevertheless, several challenges[20] should be addressed when FP is applied in audio. That is, the assessors should be carefully selected, based on their general sensory abilities and background,[20] as the quality of the given descriptors is highly important.[65] One should note that FP is not intended to provide a robust attribute vocabulary. Here a number of steps were followed to improve this limitation of the FP protocol, e.g., by introducing a short interview where definitions were given, and by recruiting highly experienced and product-expert assessors. Moreover, stimuli-anchors were added in the experimental design and a careful statistical analysis was followed.

The use of different program types is necessary for audio evaluation.[40] Thus, the stimulus that one aims to evaluate is the product of a program (i.e., speech) and an acoustical modification (i.e., spectral alteration). This is not a parameter that FP and the associated statistical methods account for imposing practical and statistical challenges.[20] For example, FP requires all stimuli to be available to the assessor simultaneously. During attribute elicitation, this could be accommodated. However, during the ranking phase, a block design is followed as the acoustical conditions must be evaluated for each program material separately.[40] In consequence when analyzing the results, one should follow statistical procedures that allow a two-way interaction between the program and the condition used. Here, the data were averaged across program levels before the final MFA analysis to overcome this limitation,[66] as no significant difference between program levels was identified. Hierarchical clustering was then used to obtain the common perceptual constructs within the collected data and enable an interpretation of the results at the panel level. The two analyses were then merged in the form of a biplot. That is, the data-based solution of factor scores, based on the stimuli rankings, and the perceptual constructs identified via attribute clustering, indicates the direction of the explained variance.

The current results provided evidence that the proposed method allows the perceptual assessment of audio material within car cabins, and contributed to our knowledge of cabin acoustics. It depicted the importance of several surfaces of car's interior and the perceptual relationships to such changes. The investigation assessed a limited number of acoustic modifications in the cabin, aiming to explore cabin acoustics and assess the applicability of the method in the automotive environment. It is, however, the first time that such an investigation is conducted in car cabins. Thus, further validation studies should be conducted. Further studies will improve our knowledge of car cabin acoustics and identify ways to compensate for the related sound degradation. Moreover, objective metrics such as spatiotemporal analysis[37] could supplement the perceptual data presented here, as shown previously.[20,26] This would allow a better understanding of the acoustical fields and robust investigation, supported by both physical and perceptual metrics.

Future work includes the investigation of several cabin acoustics and systems, as well as the application of the method in other acoustical environments, for example, small-sized residential rooms and listening spaces.

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