



Direction Specific Analysis of Psychoacoustics Parameters inside Car Cockpit: A Novel Tool for NVH and Sound Quality

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Abstract

Psychoacoustics parameters are widely employed in automotive field for objective evaluation of Sound Quality (SQ) of vehicle cabins and their components. The standard approach relies on binaural recordings from which numerical values and curves are calculated. In addition, head-locked binaural listening playback can be performed. The Virtual Reality (VR) technology recently started to diffuse also in automotive field, bringing new possibilities for enhanced and immersive listening sessions, thanks to the usage of massive microphone arrays instead of binaural microphones.

In this paper, we combine both solutions: the principal SQ parameters are derived from multichannel recordings. This allows computing a map of direction-dependent values of SQ parameters. The acquisition system consists in a spherical microphone array with 32 capsules and a multiple-lens

camera for capturing a panoramic equirectangular background image. The audio recording is encoded into High Order Ambisonics (HOA) format for being compared with a classic omnidirectional microphone and into Spatial PCM Sampling (SPS) format for producing 360° equirectangular color maps. The SPS encoding is used to plot over the background image the distribution of SPL values in dB (A) and of the SQ parameters: by adding to them the directional information, it results into a novel 360° diagnostic tool for localizing the most annoying sources.

Furthermore, the playback of the HOA soundtrack can be performed both on a loudspeaker rig inside an Ambisonics listening room or on binaural headphones attached to a Head Mounted Display (HMD), benefiting from head-tracking and personalized Head Related Transfer Functions (HRTFs), allowing to make quick subjective evaluations with a degree of realism unattainable with the older static binaural approach.

Introduction

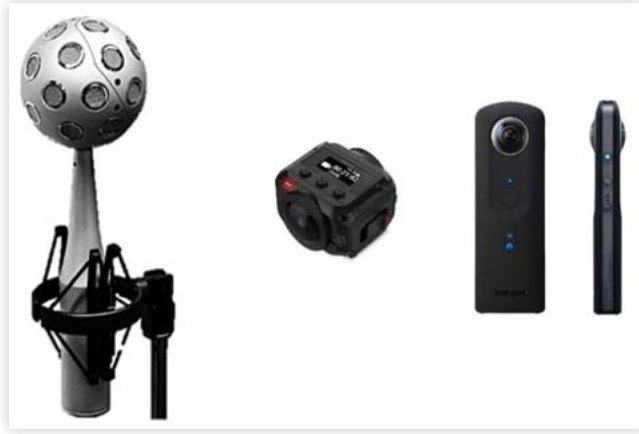
First attempt to objectify the pleasantness of sound inside a vehicle dates back to 1985, thanks to the work of Toyota engineers [1], while in 1987 the binaural measurement methodology has been defined [2]. In 2001, it has been published a paper describing a complete noise and vibration simulator [3]: the usage of a virtual environment allows reproducing faithfully the experience of being inside a car, even if the vehicle has not been built yet and providing to all members of a jury exactly the same stimuli. In 2003, Gonzales et al. employed SQ parameters to evaluate the performances of an ANC system in a car [4].

Despite the success of the traditional binaural technology, several drawbacks are inherent in this approach. If a dummy head is employed, the reproduction relies on its HRTFs, which do not fit for every possible listener. Anyhow, the playback on headphones does not benefit of head-tracking, therefore the localization of noise sources is poor. The authors already discussed the importance of employing personalized HRTFs for binaural rendering with head-tracking in [5].

In this work, the Sound Quality parameters are derived from modern VR multichannel recordings of the noise inside a car cockpit or in the environment. The acoustic spatial information is recorded employing the Eigenmike32™ (EM32), a studio-quality array of microphones (Figure 1, left), based on the pioneering work of Gary Elko [6]. It features 32 capsules arranged over the surface of a rigid sphere with a diameter of 84 mm. The visual spatial information can be recorded with a Garmin VIRB 360 (Figure 1, center) or a Ricoh Theta S (Figure 1, right), dual-lens 360° panoramic cameras, capable of taking both pictures and videos. Thanks to the two hemispherical lenses, they provide an equirectangular projection of the background images up to 5.7K or 4K resolution respectively. The effectiveness of the proposed method has been demonstrated by evaluating two different applications: a laboratory recording of artificial noise sources inside a room and a field recording at constant speed of the interior noise of a car equipped with a feedforward active Road Noise Control system (RNC).

The number of SQ parameters has considerably grown in the last thirty years as a new specific one was developed for

FIGURE 1 Eigenmike32™ microphone array (left); Garmin® VIRB 360 (center) and Ricoh Theta S® (right) 360° cameras.



almost every noise problem. The most frequently used parameters in automotive sector are loudness, fluctuation strength, roughness, sharpness, kurtosis and tonality. In this work, the color maps analysis of the recorded sound fields is focused on loudness and sharpness.

Spatial Audio Theory Recall

The use of microphone arrays has a long history in the field of “spatial audio”, dating back to the seventies, when it was developed the Ambisonics method [7]: a technique that describes the complete acoustical spatial information of the sound field in the measurement point. The Ambisonics format is obtained by encoding the signals recorded by the capsules of a dense microphone array into a set of virtual microphones having directivity patterns described by Spherical Harmonics (SH) functions (Figure 2). SH are mathematical functions of various orders, with orthonormal properties. In [8], the authors presented an explicit formulation of the SH functions up to order five. The Ambisonics format employed in this paper follows the standard AmbiX [9], hence with SN3D normalization and ACN channel numbering.

As Ambisonics is the spatial equivalent of the Fourier representation of a time-domain waveform, Spatial PCM Sampling (SPS) format [10] can be thought as the spatial equivalent of time PCM sampling. Instead of using SH, SPS employs many unidirectional super-directive microphones, covering uniformly the surface of a sphere (Figure 3), aiming to capture the complete spatial information. The directivity Q of SPS virtual microphones is given by equation (1):

$$Q(\theta, \varphi) = [P + G \cos(\theta) \cos(\varphi)]^O \quad (1)$$

where P and G are the coefficients, from 0 to 1, respectively of Pressure and Particle Velocity, that define the type of virtual microphones; O is the order of the virtual microphones; θ , φ are the angles (azimuth and elevation) between the aiming direction of the virtual microphones and the Direction of Arrival (DoA) of the sound wave. The type and the order of

FIGURE 2 the first 16 Spherical Harmonics, corresponding to Ambisonics 3rd order.

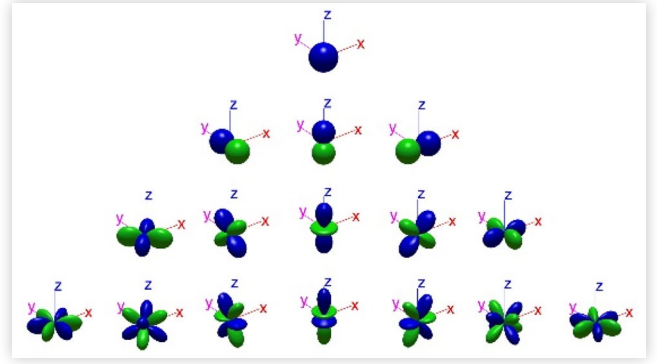
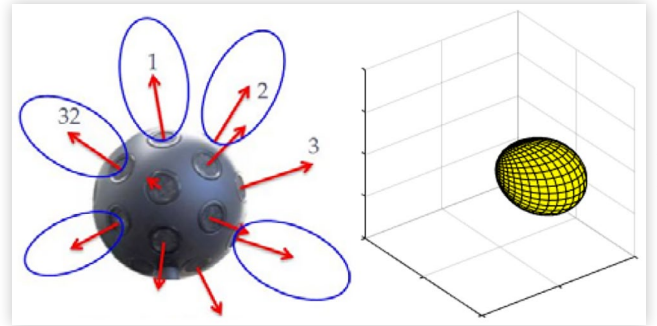


FIGURE 3 SPS-32 virtual microphones for the Eigenmike32™ (left) and the 3D directivity plot of a SPS virtual cardioid of fourth order encoded for the EM32 in the octave band centered at 500 Hz (right).



the virtual microphones must be chosen ensuring a reasonably uniform coverage of the unit sphere, depending on the number V of SPS signals. In the case of a set of 32 virtual microphones, a commonly accepted choice is cardioid of fourth order: $P = G = 0.5$ and $O = 4$.

In this study, the raw signals recorded by the capsules of the microphone array, which is usually known as “A-format”, have been converted into the two described formats. This processing, named *encoding*, is operated with a matrix of FIR filters [11], obtained with a Least Square solution of the Kirkeby Inversion:

$$|H[k]|_{M \times V} = \frac{|C[k]|_{M \times D}^* \cdot |Q[k]|_{D \times V} \cdot e^{-j\pi k}}{|C[k]|_{M \times D}^* \cdot |C[k]|_{D \times M} + \beta[k] \cdot |I|_{M \times M}} \quad (2)$$

where k is the frequency index, M is the number of capsules of the array (32), D is the number of directions employed to characterize the array response, V is the number of Virtual Microphones, $|C[k]|$ is the array response, $|Q[k]|$ is the matrix of target directivity patterns, and β_k is a frequency dependent regularization parameter.

The encoded format is given by the convolution between the recorded signals and the beamforming matrix $|H[k]|$, that must be chosen accordingly to the purpose of the processing. High Order Ambisonics can be employed for the playback over a loudspeakers rig in a listening room or for binaural reproduction over headphones attached to HMDs, with

head-tracking and eventually personalized HRTFs. In this work, the first Ambisonics channel, which is a virtual microphone with omnidirectional directivity, has been used to calculate single values of SPL [dB (A)], Loudness [sone] and Sharpness [acum] to be compared with the ones obtained employing a standard omnidirectional Bruel&Kjaer microphone. SPS format instead is employed to feed a Matlab software developed to generate 360° color map of Sound Pressure Level (SPL) [12]. The second approach will be used also for the spatial mapping of SQ parameters “Loudness” and “Sharpness”.

Direction Specific Loudness and Sharpness

Loudness, whose measurement unit is called *sone*, is a psycho-acoustic metric that quantifies the human hearing perception of the loudness of a sound. The range of audible frequencies is divided into 24 critical bands using the Bark scale, as proposed by Zwicker [13, 14]. The specific loudness is the loudness computed on a single critical band. The total loudness is obtained by integrating all the specific loudness values over the critical bands. Loudness can be calculated with two methods that use the Zwicker's algorithm [15]. They are both described in the ISO 532-1 standard [16]. The first method, which is based on DIN 45631 [17], is intended for stationary sounds. The second one, based on the DIN 45631/A1 [18], is addressed to arbitrary time-varying sounds, including stationary sounds as a special case.

Sharpness, whose measurement unit is the *acum*, quantifies the sensation caused by the content at high frequencies in the analyzed signal. Note that one *acum* corresponds to the sharpness of a narrow band noise at 1 kHz, with bandwidth less than 150 Hz and SPL level of 60 dB. The current DIN 45692 standard governing the calculation of sharpness [19] is based on the work of Widmann [20].

The Direction Specific Sound Quality (DSSQ) parameters are rendered through color maps. In order to generate the color maps, loudness and sharpness values must be calculated from each of the 32 virtual microphones, obtained by encoding in SPS format the raw signals recorded by the Eigenmike32™. This operation has been performed with a software written in Matlab and employing the functions developed by the research group in acoustics of Salford Innovation Research Center (SIRC) for calculating Loudness and Sharpness [21], respectively based on [18] and on [15]. The implemented method for Loudness calculation is the one concerned to stationary sound described in [16]. It allows to use third octave-band levels as input.

Field Applications

In the following paragraphs, two experiments performed with the new method and their results are presented: an indoor test and an in-car test.

Indoor Laboratory Test

The recording of an artificial noise source has been performed in a generic indoor environment (the acoustic laboratory at University of Parma). It is approximately a 7x7x3 meters room without any specific absorbing or reflecting treatment. A pink noise signal was played through a full-band point-source loudspeaker (Genelec™ Studio Monitor 8351A), while a tone at 4.5 kHz was played through the micro-speaker of a smartphone. The pink noise signal played with the loudspeaker emulates a background noise, while the micro-speaker emulates a point source emitting an annoying sound. In the recording position, which is located at the same distance of 1.9 m from the two sources, the SPL produced by each source playing alone has been measured with a Sound Level Meter (SLM). The measurement results were 70.8 dB(A) for the pink noise and 66.2 dB(A) for the tone. Then the SLM has been replaced with the EM32 and a recording of 30 s has been taken with the two sources switched on simultaneously. Finally, the EM32 has been replaced with the Ricoh Theta S, keeping the acoustic and optical centers at the same height (1.4 m) in order to avoid any offset, which would cause a mismatch between the color maps and the background image.

The A-weighted color map of SPL has been produced (Figure 4). One can note that the emulated background noise produced by the loudspeaker is completely masking the disturbing tone, which instead was played simultaneously by the micro-speaker of the smartphone (highlighted in the red circle).

In Figure 5, it is possible to see both sound sources in a SPL map filtered in the octave band centered at 4 kHz. The Loudness map has been calculated (Figure 6) and, as expected,

FIGURE 4 SPL color map, [dB (A)].

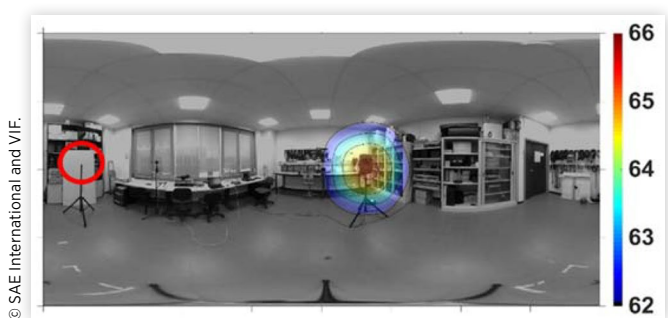


FIGURE 5 SPL color map filtered in the 4kHz octave band, [dB (A)].

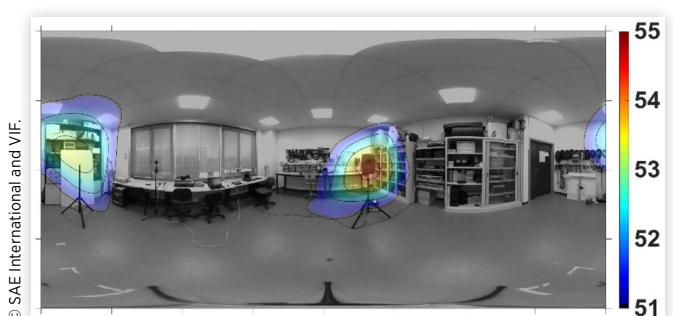


FIGURE 6 Total Loudness map of a pink noise source and a disturbing tone, [sone].

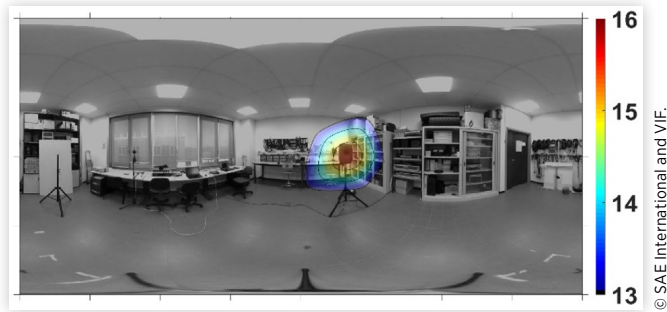


FIGURE 7 Sharpness map of a pink noise source and a disturbing tone, [acum].



it provides the same information of the A-weighted SPL map: the broadband noise source is localized, as no low frequencies are emitted by the micro-speaker. Finally, the Sharpness map is calculated (Figure 7): the annoying tonal source is perfectly localized, excluding completely the broadband background noise source.

Car Cockpit Test

The proposed method has been evaluated with a second test performed on a car equipped with an ANC system. For this application, the usage of SQ metrics can be very useful to assess either the effectiveness of the ANC system to reduce the noise level and its capability to improve the sound experience inside the vehicle. In addition to the standard approach, which relies on punctual values calculated from measurements taken in one or two positions (omnidirectional or binaural microphones), typically close to the occupant's ears, the usage of a technique based on spatial sound information can be a great support for the development of these systems. In fact, the analysis of the spatial distribution of psychoacoustics parameters could provide additional information with respect to the standard SPL map, as the processed quantities are different and tailored to better qualify and quantify the human sound perception.

A C-segment car equipped with a 4-seats feedforward accelerometer-based Road Noise Cancellation system (RNC), developed by ASK Industries S.p.A. and previously described in [22], has been measured with the new DSSQ approach. A mannequin torso supporting the EM32 and a 360° camera is positioned on the front passenger seat (Figure 8). The vertical

FIGURE 8 the EM32, the Garmin™ Virb 360° camera and the reference omnidirectional microphone mounted in the car.

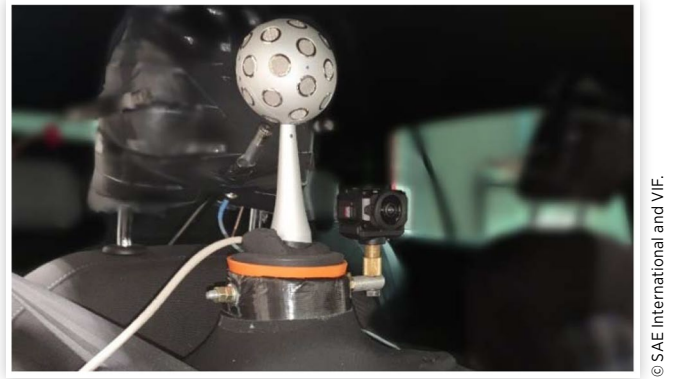
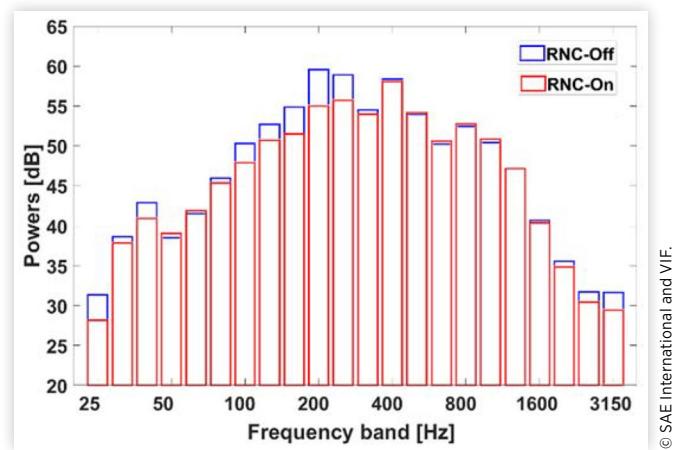


FIGURE 9 One-third octave spectra for RNC-Off and RNC-On conditions with the Reference Omnidirectional Microphone, [dB (A)].



offset between acoustics and visual centers is realigned in post-processing. The EM32 position is approximately the same one of the head of a passenger seated in the car. The audio and video signals recorded with this setup can also be used for out-of-the-car listening tests and subjective evaluation of almost every NVH or audio infotainment assessment scenarios, as the authors have already presented in [5].

In order to compare the new proposed system with the standard methodology, an additional omnidirectional measurement microphone (B&K™ Type 4189 capsule with Type 2671 preamplifier) has been mounted on the seat headrest, placing the capsule near the EM32 sphere. A ZOOM™ F6 Multi Track Field Recorder with digital gain control has been used to record the single point signal. This reference omnidirectional microphone has been calibrated with a pure tone of 94 dB at 1 kHz with a microphone calibrator B&K™ Type 4230.

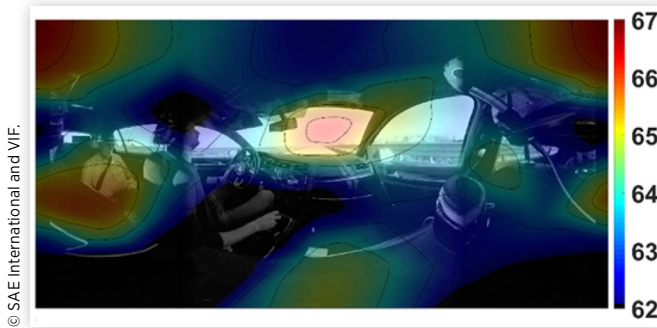
Two test recordings of 40 s have been taken on the same straight rough road at 70 km/h with the RNC system switched off (RNC-off) and then switched on (RNC-on). The RNC system is mostly effective on the structure-borne road noise at low frequency, as it is displayed in the third-octave A-weighted spectrum of Figure 9, calculated on the reference

TABLE 1 SPL single values calculated on band-pass filtered (20 Hz -400 Hz) signals for RNC-off and RNC-on conditions with Eigenmike32™ and Reference Omnidirectional Microphone, [dB (A)].

SPL [dB(A)] (20-400 Hz)	RNC - off	RNC - on
Ambisonics W channel EM32	64.3	61.9
Ref Omnidirectional Microphone	64.8	62.2

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FIGURE 10 SPL color map for RNC-off condition, band-pass filtered (20 Hz - 400 Hz), [dB (A)].



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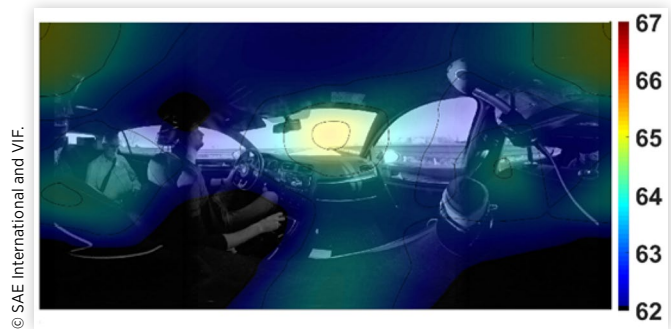
omnidirectional microphone for the two conditions (RNC-off and RNC-on). For the further processing, both SPS format and reference omnidirectional microphone signal have been band-pass filtered in the frequency range 20 Hz – 400 Hz, where the RNC system proved to be more effective. Consequently, the frequency range of interest is low enough also to ensure that interference between the EM32 and the reference omnidirectional microphone, which are mounted close each other, can be neglected and the two systems can be considered acoustically coincident.

The first Ambisonics channel (W) and the signal recorded by the Reference Omnidirectional Microphone, equally filtered in the frequency range 20 Hz - 400 Hz, have been used to calculate single values of SPL [dB (A)], which are shown in Table 1. The variation of SPL values between the two conditions (RNC-off and RNC-on) is, respectively for the two methods, 2.4 [dB(A)] and 2.6 [dB(A)]. A difference of 0.2 [dB(A)] between the two methods is negligible and this lead to assess that the proposed solution can be considered consistent with respect to the standard method.

The SPS signals have been encoded from the signals captured by the capsules of the EM32 and employed to plot the A-weighted SPL color maps in the two working conditions, RNC-off (Figure 10) and RNC-on (Figure 11). Although the spatial resolution of the array is limited in the analyzed frequency range, it is clearly noticeable a SPL reduction of approximately 2.5 dB(A), without significant changes of the sound field pattern.

The band-pass filtered signals are then analyzed with the SQ metrics. The total loudness single values (Table 2) have been calculated for each working condition employing the first Ambisonics channel (W) encoded with the EM32 and the reference omnidirectional microphone. The variation of the Total Loudness values between the two conditions of RNC system Off and On is, respectively for the two systems,

FIGURE 11 SPL color map for RNC-on condition, band-pass filtered (20 Hz -400 Hz), [dB (A)].



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TABLE 2 Total Loudness single values calculated on band-pass filtered (20 Hz - 400 Hz) signals for RNC-off and RNC-on conditions with Eigenmike32™ and Reference Omnidirectional Microphone.

Total Loudness [sone] (20-400 Hz)	RNC - off	RNC - on
Ambisonics W channel EM32	11.7	10.3
Ref Omnidirectional Microphone	12.7	11.2

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1.4 [sone] and 1.5 [sone]. A difference of 0.1 [sone] between the two methods can be considered negligible and it confirms the consistency with respect to the standard method.

The comparison between the two working conditions, recorded with both systems (EM32 and the reference omnidirectional microphone), shows that the RNC system provided an improvement of the sound quality, as the Total Loudness is reduced by more than 1 [sone]. It is assumed that the values calculated employing the EM32 are more reliable, as they are the result of a spatial sampling over a volume, instead of a single point evaluation. However, the Total Loudness single value gives just a score of the performance and it does not offer any information on how the sound field modification occurs.

In Figure 12 and Figure 13, the specific loudness spectra for the two working conditions are shown for the Ambisonics Omnidirectional channel (W) obtained from the EM32 and the reference omnidirectional microphone, respectively. This confirm that the two recording systems are sensing the acoustic sound field in the same way and they are comparable.

The Total Loudness color maps have been calculated for the two working conditions (Figure 14 and Figure 15). Note that the Loudness comparison provides similar information with respect to the A-weighted SPL color maps. Nevertheless, the Loudness color map renders better the human perception of switching the RNC system On and Off.

The singles values for the Sharpness parameter have been calculated (Table 3) with the previously described methodology. A little increment can be observed with both methods switching the condition from RNC-off to RNC-on, respectively of 0.007 [acum] for the EM32 and 0.002 [acum] for the reference omnidirectional microphone. It is an expected behaviour, related to the reduction of energy at low frequencies provided by the RNC system; nevertheless, the variation can be considered negligible. This is a great result: the RNC system provides an improvement of the Sound Quality of the

FIGURE 12 Specific Loudness for Ambisonics W channel EM32, band-pass filtered (20 Hz - 400Hz).

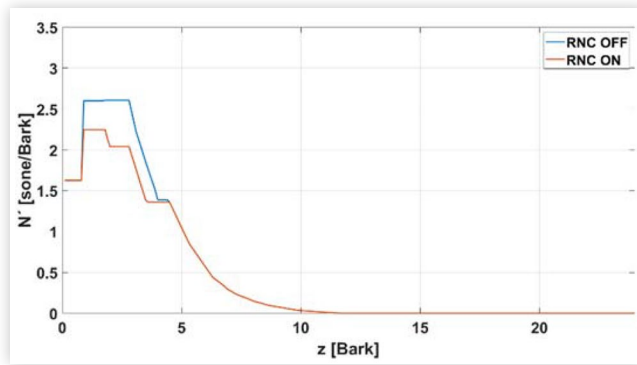


FIGURE 13 Specific Loudness for Reference Omnidirectional Microphone, band-pass filtered (20 Hz - 400 Hz).

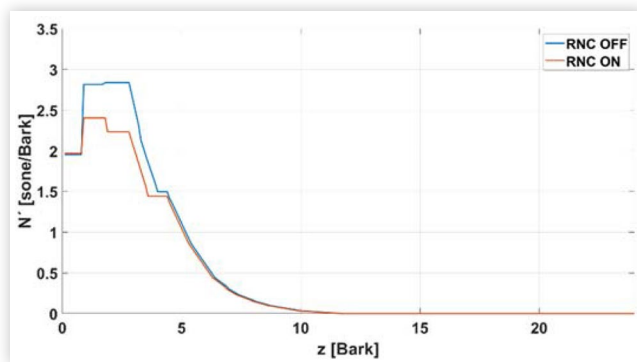
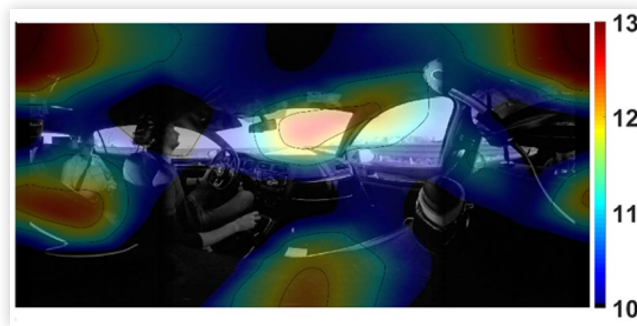


FIGURE 14 Total Loudness color map for RNC-off condition, band-pass filtered (20 Hz - 400 Hz), [sone].



passenger compartment reducing the Loudness by at least 1.4 [sone] without causing any worsening of the Sharpness parameter. In addition, being the behaviour of the two methods identical, also in this case it is possible to assess that the proposed solution is consistent with respect to the standard method.

The Sharpness color maps have been calculated for the two working conditions (Figure 16 and Figure 17). As for the single values, also the Sharpness color maps do not highlight significant sound spatial pattern changes or increasing between RNC-off and RNC-on conditions.

FIGURE 15 Total Loudness color map for RNC-on condition, band-pass filtered (20 Hz - 400 Hz), [sone].

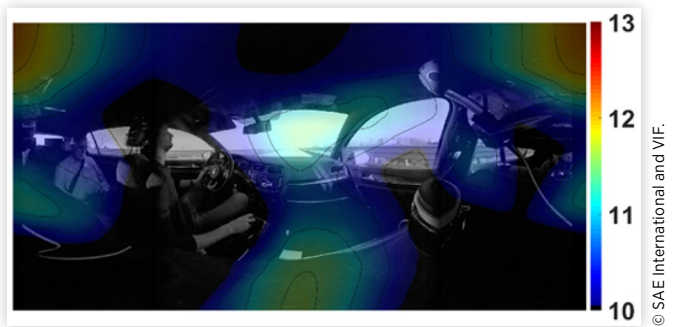


TABLE 3 Sharpness single values calculated on band-pass filtered (20 Hz - 400 Hz) signals for RNC-off and RNC-on conditions with Eigenmike32™ and Reference Omnidirectional Microphone.

Sharpness [acum] (20-400 Hz)	RNC - off	RNC - on
Ambisonics W channel EM32	0.3194	0.3263
Ref Omnidirectional Microphone	0.3148	0.3169

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FIGURE 16 Sharpness color map for RNC-off condition, band-pass filtered (20 Hz - 400 Hz), [acum].

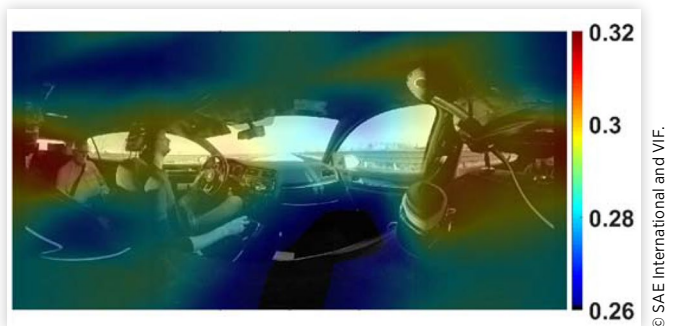
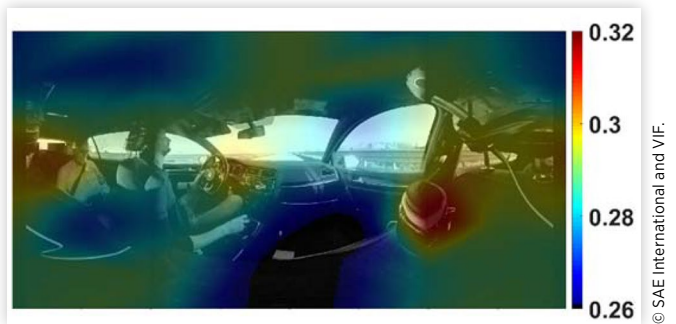


FIGURE 17 Sharpness color map for RNC-on condition, band-pass filtered (20 Hz - 400 Hz), [acum].



The very slight increase of the red spot in Figure 17, corresponding to the direction of the rear door woofer loudspeaker, is due to the cancelling effect of the RNC system in a region where the SPL level of noise [dB (A)] with RNC-off condition and thus the Loudness are already very low (Figure 10 and

Figure 14). In this specific direction, the unmasking of higher frequencies is slightly pronounced, resulting in a little increase of the Sharpness parameter.

Conclusions

The novel audio/video recording system proved to be effective for analyzing the spatial distribution of psychoacoustics parameters. The color mapping software allowed to produce pseudo-color maps of loudness and sharpness parameters superimposed on a high-resolution background image.

Experimental evidence was given of the performance of the proposed solution, making use of the Eigenmike32™, which is recognized as the reference microphone array in the last decade for spatial audio recordings. The array was used in two field tests: in both cases, depending on the specific condition, the Direction Specific Sound Quality color maps confirmed their capability of providing more information and spatial accuracy than the SPL color maps.

A Sharpness map proved to be effective for localizing an annoying high frequency source, which was masked by the background noise, as shown with SPL [dB (A)] and Loudness color maps, and that was not uniquely individualized with a SPL [dB (A)] octave band filtered color map.

The Sound Quality improvement provided by a RNC system installed on a car has been demonstrated making use of the Loudness and Sharpness color maps. As expected for this type of system, the Loudness map confirmed the results provided by the SPL map. The Sharpness map ensured that the parameter has not significantly worsened in any specific direction.

Furthermore, the single values of the overall psychoacoustic parameters and their variations between the two conditions RNC-off and RNC-on, obtained employing a standard equipment, a reference omnidirectional microphone, resulted to be very close to those obtained by means of the new proposed solution, a microphone array processed with a proper beamforming matrix. The presented processing algorithm improves the reliability, as the overall values are measured employing several microphones distributed in space, instead of a single measurement point.

A detailed comparison among the standard methodologies (omnidirectional and binaural microphones) against the proposed system, also employing additional sound quality parameters, is planned and it will be the subject of next works.

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