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Vibrations' influence on Dieselness perception

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ABSTRACT

Up to now, different studies dealing with vibrations' influence on acoustics have been, in most cases, realized on global annoyance. In our case, the present study examines the vibrations' influence on the auditory perception of Diesel character (called Dieselness in this article) of a vehicle. In addition, cultural experience is evaluated by testing two groups of Diesel owners from two European countries (respectively France and Germany). During the experiment, each population was exposed to sound only, and sound and vibrations simultaneously. This perceptual test was realized on a vibration bench (driver seat and steering wheel) with headphones. Three kinds of vehicules and six different driving situations have been tested. Results reveal no differences between French and German. Nevertheless, the adding of vibrations influences the Dieselness evaluation. The participants give slightly higher scores (more Diesel) or equal (as Diesel) with vibrations than without. However, this vibration effect is slightly dependent on the type of vehicles and on the driving situations and it appears less important for German people. In addition, for each group of participants, the other factors vehicle and driving situation have an effect on Dieselness assessment. The effect of vehicle allows to show that 3 cylinders car is significantly different from 4 cylinders and 6 cylinders cars. Finally, the interaction between driving situation and vehicle shows the strongest effect on Dieselness evaluation, among all interactions tested. The vehicle effect is dependent on the driving situation. All results and conclusions have to be taken with care in order not to generalize for all similar classification cars.

1. Introduction

Even without taking into account sound, vibration perception is a very complex topic. Indeed, different random parameters, like postures and participants' sensitivity contribute, among others, to this perception. In addition, the main reason of this topic's complexity lies in the difficulty to reproduce in details previous studies. There is a great disparity between various experimental contexts [1–3]: level and dynamic of vibrations, artificial or real sources, frequency range of stimuli or test methodologies, differ.

The common basis of studies about vibrations is the use of a bench made up of a platform with a seat and sometimes even, a steering wheel [4–6]. Nevertheless, the different authors do not take into account same degrees of freedom: a majority limits their vibration reproduction in the vertical plane along the z-axis for the seat [7–9].

By taking into account the whole modalities, the possibilities of experiments are numerous: vibration effect on noise assessment, effect of sound stimulus on vibration appraisal or also, effect of both on the overall evaluation of a parameter (such as comfort for instance [10]). Most studies about this interaction focused on their influence on the perception's threshold (of sound or of vibrations) [11,12]. Indeed, studies of Weber et al. [12] and Bellmann [13] conclude about no significant influence of sound on the perception's threshold of vertical vibrations. With a study about vibrations influence on the loudness assessment, Parizet et al. [9] show the lack of vertical vibrations influence on this loudness evaluation. Conversely, they indicate that a sound stimulus impacts significantly the vibrations level's assessment. Besides, Amari [14] evokes a "*synergistic effect*": the higher the noise level is, the higher the vibration level is considered. In a different register with sound influence on vibrations level's assessment, Miwa and Yonekawa [15] showed that there is no significant effect on it. However, they join Parizet's conclusion on the fact that with a high noise level, vibration level is overestimated.

Other kinds of studies focused on discomfort (or annoyance) assessment [1,16–18], especially for idle driving situation

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[2,4,5,7,17,19]. It has been observed that both modalities can contribute equally to comfort until one becomes highly dominant [17]. The overall sensation seems to be dominated by the more annoying or stronger modality. Besides, Bellmann [13] concludes that there is a state of "balance" to be observed between vibration intensity and sound intensity, expected by drivers. Also, Leatherwood [10] showed that contribution of each modality depends on their respective levels. But their interaction is clear: for vertical vibration levels which affect (in a negative way) the comfort, the add of a sound has little influence. However, with a weak vibration level, the increasing of the noise level raises noticeably the discomfort assessment.

Moreover, comfort issue is a scientific topic often treated in the transport domain (automotive and rail industries). Parizet et al. [17] and Howarth and Griffin [1] have two examples of this kind of studies. Indeed, the first one has realized an experiment in three stages: the discomfort's assessment of a sound stimulus alone, the discomfort's assessment of a sound presented to the participants with a vibro-acoustic stimulus and finally, global discomfort's evaluation of the vibro-acoustic stimulus. Results prove that vibrations have a small but significant influence on sound assessment. For some participants, the overall annoyance is only related to vibrations while for others, it seems to be linked to both modalities. In their study, Howarth and Griffin [1] focused on the discomfort's evaluation caused by sounds and vibrations generated when a train passes close to a domicile. They conclude that vibrations do not affect the annoyance rating. Conversely, noise influences discomfort appraisal due to vibrations according to the relative magnitude of them. Therefore, discomfort caused by low vibrations decreases for higher noise levels and global discomfort is linked to relative levels of noise and vibration stimuli.

Finally, a last study, particularly interesting for our work, has been realized by Amman et al. [20] on driving situations. The participants have assessed the respective contribution of sound and vibrations (with six degrees of freedom) on assessments of driving situations (unsteady ones or passing on small obstacles) reproduced in a simulator. The experiment, linked to a preference issue, shows that the contribution of each modality is equivalent to the total preference evaluation of a driving situation.

As we have seen, the great diversity of studies conducted with sounds and vibrations makes it difficult to compare them. One can still conclude that a large number of the researchs agree that global discomfort of a studied parameter depends on both modalities.

In the present study, we focus on vibrations' influence concerning Dieselness issue. Indeed, Diesel vehicle is one of many daily-life sound sources that each person may qualify according to its sensitivity. However, each person defines its own Diesel noise with its own feelings which allows him to recognize it and often to disparage it. By using Dieselness term, we want to refer to "Diesel character": what, in the stimuli (sound alone or sound and vibrations together), reminds participants of their experience with a Diesel car. Fastl et al. [21–23] define the Dieselness term as "*the typical sound character of Diesel engine*". On the contrary, we did not use this exact definition to explain the Dieselness term to participants. The instruction of experiment gave details only as following: *Up to what point does this stimulus corresponds to a typical driving situation of a Diesel car? In other words, up to what point does it call up a Diesel stimulus? Up to what point does it allow to be aware of a Diesel car?*. We have let people to keep their own definition of Diesel character.[1]

[1] In the following, we will use "Dieselness" or "Diesel character" terms to express the same idea.

This article presents results of the perceptual vibro-acoustics test about Dieselness rating of six different driving situations of three various Diesel cars. It is made up of three parts. In the first part (Section 2), data recordings and processings (of sound and vibrations) are presented. Secondly, the experiment is detailed by precising the experimental setup and the protocol (Section 3). Finally, results are presented and discussed taking into account the two populations (French and German). Do perceptual differences exist between those two European populations, known as being two countries which possess the most Diesel vehicles in their respective markets [24,25]? If yes, what are the perceptual differences between those countries? Previous studies on intercultural differences have already been realized more particularly between Europe, America and Asia which have shown some differences between those different continents [26,27]. But what happens between two countries on the same continent? Moreover, previous marketing studies between those two countries have been performed at Renault [24,25]. Results highlight the differences between the two markets by distinguishing the driving style and the bought vehicle type. Also, this study precises that French and German agree with their expectations about the vehicle and its engine. Our hypothesis about cultural difference seems to be not to find big differences between those two populations because they both belong to the Europe and they represent the most Diesel market of Europe.

2. Sound and vibrations database

2.1. Recording

Acoustics and vibro-acoustic data are recorded simultaneously. The equipment used is respectively a Head Acoustics system (HMS III dummy head) in the co-driver seat and a LMS device (Scadas SCM-05). To record vibrations, two three-axis accelerometers are used (x, y and z directions): one located on the steering wheel's hoop and the other one, on the left back side of the driver seat. Fig. 1 shows the accelerometers' position. Two outputs of the dummy head and three channels of each accelerometer are linked to the eight inputs of LMS Scadas device. According to measurement's system used, sound and vibrations' recordings have been made respectively with a 102.400 kHz and a 4.096 kHz sampling frequency. All records are realized in a same section of a test ring.

2.2. Apparatus

A simulation bench equipped with a car seat and a car steering-wheel is used during experiments. It reproduces vibrations of three directions (x, y and z) for seat and two directions for steering-wheel. Nevertheless, benches used for experiments in France and in Germany, do not reproduce the same directions for steering wheel; in France, x and z directions are reproduced whereas in

Fig. 1. Locations of the three-axis accelerometers (blue) on the steering-wheel (left side of the figure) and on seat (right side of the figure) during the vibrations' recordings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Germany there are y and z, because benches developed by ITAP GmbH are not totally similar. Structure are really close (even if French one is lighter than German one because it is more recent and some improvements have been done) but seat and steering wheel are different. For the German bench, seat and steering wheel come from VW Golf whereas for the French one, they come from Renault Mégane. Moreover, axes of steering wheel differ with y and z for German one and x and z for French one.

Measures in Table 2 shows that x is, on the average, the dominant direction, and y the less dominant one. Therefore, it may be hypothesized that the effect of the vibrations will be strongest in the French configuration. In addition, the difference between the two benches may also affect the results for other parameters of the experimental setup such as the driving situation and the type of Diesel vehicle (see Section 3.2). Thus, this difference between the two benches will be taken into account in the analysis of the results. Fig. 2 presents the French bench.

For vibrations' reproduction, twelve electrodynamic exciters generate vibrations of the platform (four shakers for each direction) and two reproduce the steering-wheel's ones. Sound stimuli are presented *via* a Head Acoustics system (HPS IV amplifier) and a Sennheiser half-opened electrostatic headphone. The whole system is driven by a computer equipped with a multi-channel sound card (RME Fireface 400). Each of the seven channels wav signals (sound stereo + three channels for seat + two channels for steering wheel) go through this sound card and Yamaha P7000S power amplifier system before exciting plateform and steering wheel. Stimuli reproduced through headphones and vibratory bench correspond to sensations that participants may experience when they are driving their car.

2.3. Processing

Different processes are applied to signals in order to prepare them for perceptual test:

1. all recordings are exported in a wav format with a 44.100 kHz sampling frequency and 16 bits quantification;
2. signals of vibrations are filtered from 20 Hz to 150 Hz for seat and from 20 Hz to 300 Hz for steering-wheel (see below);
3. all signals of vibrations are filtered with inverse transfer function of the bench.

After resampling sound and vibration data, the second treatment consists in filtering signals in two different frequency ranges.

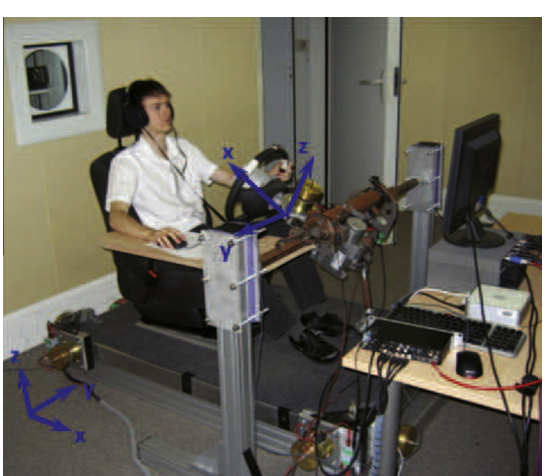

Fig. 2. Picture of the French bench. The steering wheel reproduces the x and z directions of vibrations.

Vibration signals are filtered from 20 Hz to 150 Hz for the seat and from 20 Hz to 300 Hz for the steering wheel. These choices were made for different reasons:

- *For the seat*: We have decided not to reproduce the accelerations below 20 Hz for two reasons. First, Fig. 3 shows that – in the "worst" case for the 3-cylinder car which has the strongest vibration level – the accelerations are really weak and negligible below 20 Hz for the seat (at the top) and for the steering wheel (at the bottom). Secondly, even if these frequencies exist in a driving situation, they can be overamplified – by accident – in a experimental setting. If it is the case, different studies have shown that physical disorders can appear (with resonances of stomach at 4–5 Hz, of liver at 4–8 Hz, of heart at 5–6 Hz and of kidney at 6–12 Hz [28–30]). Finally, the reasons for limitating the frequency range of the reproduction device between 15 Hz and 150 Hz are due to the fact that measurements of electrodynamic exciters show two resonances. A first and most important one around 15 Hz which corresponds to rigid body mode, and a second, weaker one around 150 Hz due to moving parts. By taking into account those three pieces of information, we limit the seat frequency range between 20 Hz and 150 Hz.
- *For the steering wheel*: Concerning the steering wheel, Barth [32] precised that it contributes strongly to the vibrations' perception especially beyond 100 Hz. In addition, Griffin [30]

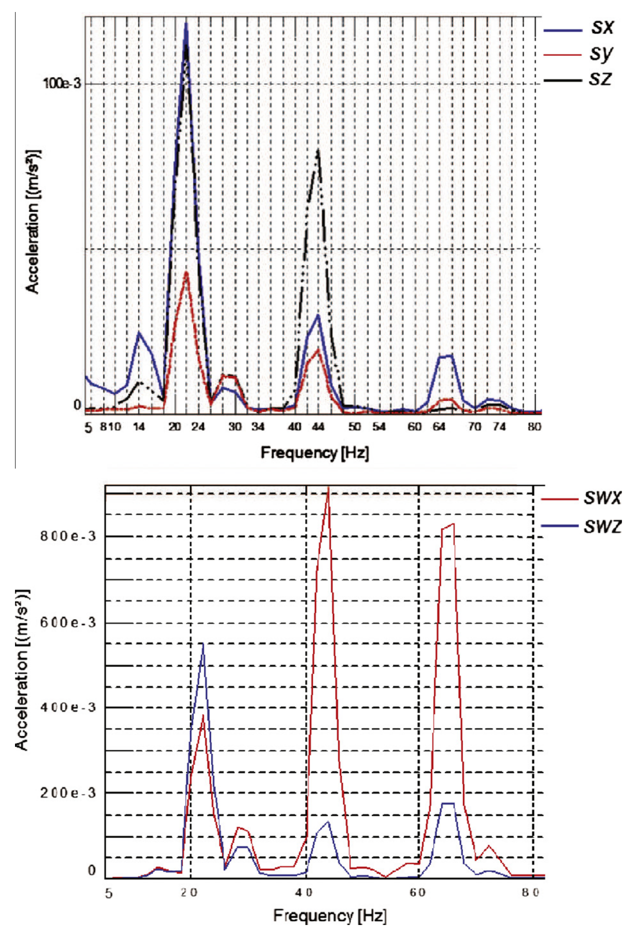

Fig. 3. Frequency responses of the bench for a 3-cylinder car *hot idle* signal (Hyundai Getz). At the top, the seat frequency response (x direction in blue, y in red and z in black) and at the bottom, the steering wheel frequency response (x direction in red and z in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

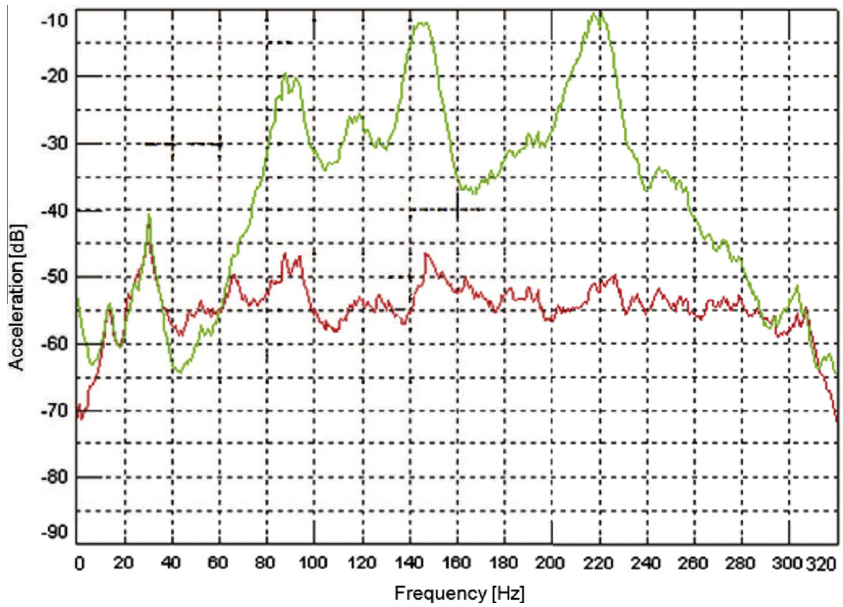

Fig. 4. Frequency response of the bench with a white noise (green curve) and with noise filtered by the inverse of the frequency response (red curve). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

highlights a sensitivity in a frequency range of 50–200 Hz for hands. Finally, Giacomin and Ajovalasit [4] precises vibrational energy can reach frequencies of up to 300 Hz and vibrational modes with large resonant peaks appear for frequencies from 20 to 50 Hz. Therefore, filtering was made from 20 Hz to 300 Hz for the steering wheel's signals.

Finally to have a reproduction as faithful as possible as in a vehicle's cabin, signals reproduced by the bench have to be the same as those recorded in vehicle. For this, we have to minimize the influence of the bench. Therefore, signals are filtered taking into account the bench's behavior. For this, measurements consist of several stages:

1. measurement of bench's frequency response to a white noise (for each of five directions: three for seat and two for steering wheel);
2. calculation of the inverse frequency response,
3. validation of the flat frequency response of the bench and check with original steady signals (measured in real conditions) reproduced with bench.

Initially, transfer function between the electrical signal from the amplifier and the acceleration from the accelerometer is recorded (for all directions, one by one). This transfer function is defined by the following equation:

$$Y(z) = X(z) * H(z) \Longleftrightarrow H(z) = \frac{Y(z)}{X(z)} \quad (1)$$

Then, in order to allow a response to be as flat as possible from the bench, the measured transfer functions have to be filtered with their inverse. First, we approximate this measure with filter coefficients a_i and b_i:

$$H(z) = \frac{a_0 + a_1 z^{-1} + \cdots + a_n z^{-n}}{1 + b_1 z^{-1} + \cdots + b_n z^{-n}} \quad (2)$$

To check effectiveness of filter, two stages have been validated. First, we use white noise filtered by transfer function's inverse and check the frequency response of the bench that gave a flat response. Secondly, we do the same validation with recordings of vehicles (steady ones), filtered in the same way. Besides, Fig. 4 shows the frequency response of the bench with a white noise (green curve) and with the same white noise filtered by the transfer function's inverse (red curve). We can see that in the red case, the frequency response is flatter. Moreover, Fig. 5 presents the cross effects measures of the platform: (a) the vibrational levels measured in the three directions when the x direction is excited by the white noise; (b) the vibrational levels measured in the three directions when the y direction is excited by the white noise and (c) the vibrational levels measured in the three directions when the z direction is excited by the white noise. Therefore, by looking at case (a), we notice that the vibrational levels measured in the direction, which is not excited by the white noise, are negligible compared to those measured in the excited direction even if some sensitive areas exist. Indeed, below 40 Hz two common modes exist between the directions x and y with similar levels. Also, between 140 Hz and 160 Hz, the measured levels of the z direction are higher. The assessment is the same for case (b) and a bit less right for case (c) where y and z directions are excited, respectively. However, despite these remarks, it was revealed to be difficult to take into account the global transfer matrix, and we have decided to apply the corrections independently to each direction, and therefore to neglect the cross-terms' influence. The approximation can be done because the levels are lower enough compared to the levels of the excited direction.

Finally, in order to reproduce signals during experiments, a seven channel wav file was created with sound stereo files and five vibrations' recordings. Each new wave file is made at a 44.100 kHz sampling frequency with 16 bit quantization.

No signal processing was applied to acoustic signals.

3. Experiment

Seventy-two stimuli are proposed to participants (6 driving situations * 3 vehicles * 2 kinds of stimuli.[2] * 2 for the repetition to check the reliability of the participants' answers). For each one,

[2] With and without vibrations.

participants have to make their Dieselness judgments on a Diesel continuous scale taking into account the global stimulus.

This test is made up of two parts. The first one (named **orientation stage**) let the person immerse into the test conditions in order to have an idea about stimuli's basis. The second one (named **evaluation stage**) refers to the Dieselness evaluation for all stimuli, one by one. All stimuli are presented in a random order.

The main goal of this experiment is to focus on vibrations' influence on Dieselness perception. As this experiment took place in two countries (France and Germany), a cross-cultural approach is highlighted in this article.

3.1. Participants

This experiment was performed in two countries: France and Germany. 35 participants in each country took part in this experiment. For the recruitment, people had to correspond to some criteria. They had:

- not to work in automobile or acoustics domains,
- to be Diesel owners and use it regularly (daily or several times per week),
- to be devoid of hearing problems.

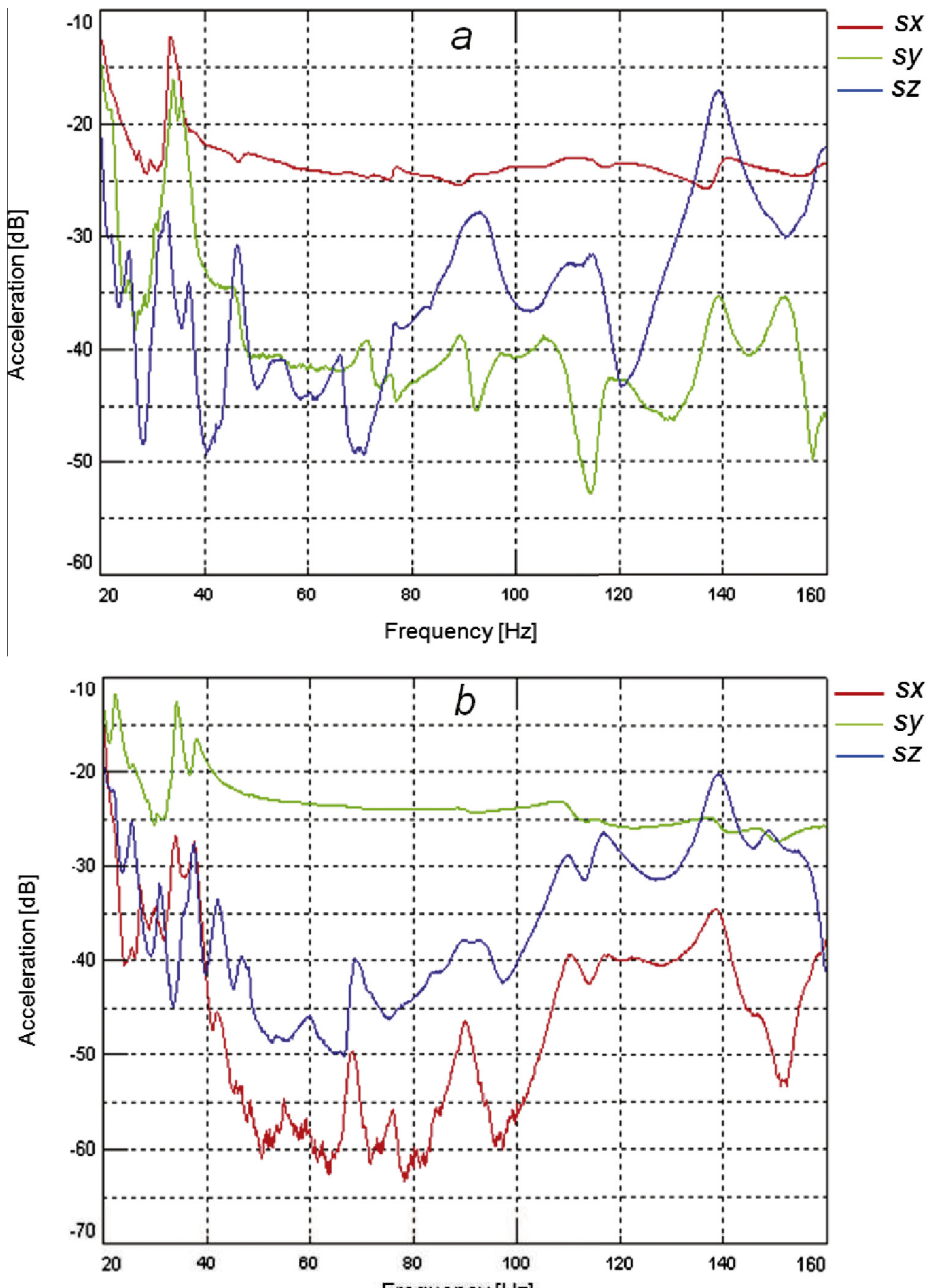

Fig. 5. Cross effect of the platform: (a) vibrational levels measured in the three directions when the *x* direction is excited by the white noise; (b) vibrational levels measured in the three directions when the *y* direction is excited by the white noise and (c) the vibrational levels measured in the three directions when the *z* direction is excited by the white noise.

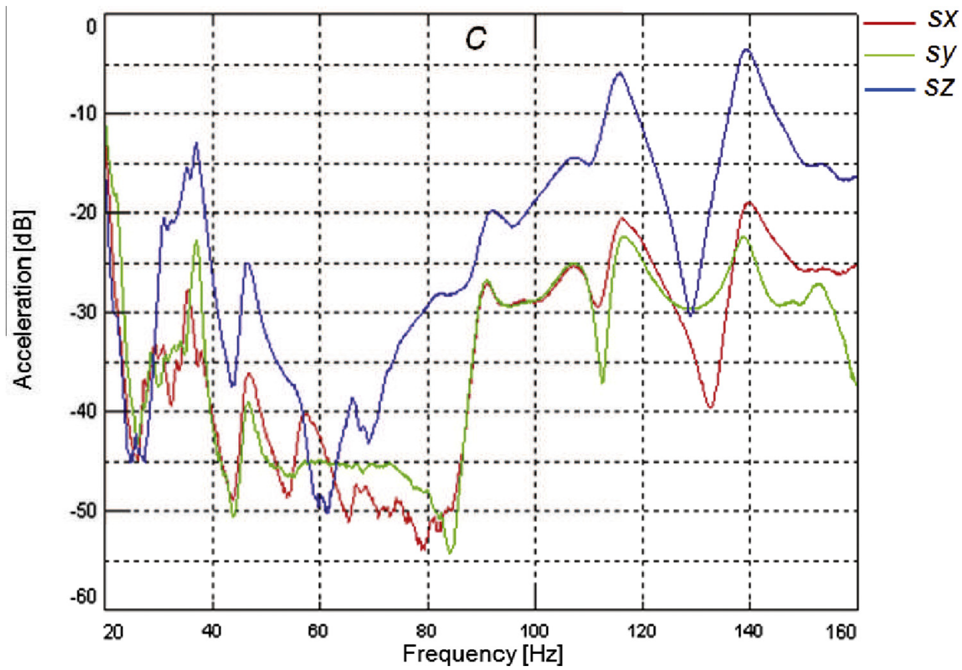

Fig. 5 (*continued*)

Table 1
Anthropometric data – means and standard deviations in brackets – of French and German participants.

	Gender		Mean		
	Men	Females	Age (yo)	Body-size (cm)	Weight (kg)
French	21	14	43 (10)	172 (11)	75 (13)
German	26	9	29 (11)	178 (11)	80 (11)

Table 1 summarizes informations (gender, mean age and anthropometric data like body-size or weight) about the 70 participants. The mean time duration needed by the participants for the whole test is 34 min for French and 39 min for German with standard deviations of 3.2 min and 4.2 min respectively.

3.2. Stimuli

Six different driving situations (from three different Diesel cars) were presented to participants: *hot idle*, *90-kph*, *start up the motor*, *stop the motor*, *acceleration* and *deceleration*. Those driving situations have been chosen in order to propose to the participants driving situations known and used by all, in a daily-life. The three different Diesel vehicles are a 3 cylinders in line (C1), a 4 cylinders

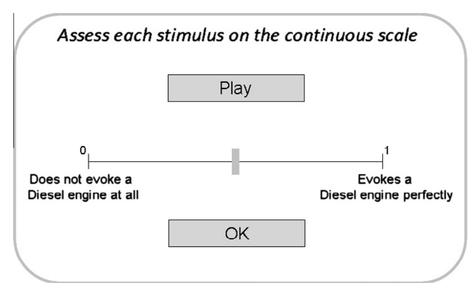

Fig. 6. Example of the direct evaluation during the experiment (play the stimulus at the top, assess it in the scale at the middle and validate the choice with "OK" at the bottom).

Table 2
Metrics' table for six driving situations and three vehicles (C1: 3 cylinders car, C2: 4 cylinders car and C3: 6 cylinders car).

Vehicle	Situation	s_x	s_y	s_z	sw_x	sw_y	sw_z	L_{dB}
C1	Hot idle	0.08	0.10	0.11	0.49	0.46	0.42	102.45
	90-kph	0.04	0.04	0.05	0.45	0.22	0.36	107.61
	Start up	0.01	0.03	0.02	0.20	0.12	0.13	103.03
	Stop	0.07	0.08	0.10	0.44	0.26	0.35	98.89
	Acceleration	0.03	0.03	0.02	0.48	0.18	0.28	110.96
	Deceleration	0.03	0.03	0.03	0.41	0.18	0.32	109.79
C2	Hot idle	0.1	0.07	0.05	0.68	0.47	0.55	92.29
	90-kph	0.02	0.03	0.03	0.56	0.40	0.40	105.74
	Start up	0.03	0.05	0.04	0.54	0.27	0.4	96.83
	Stop	0.03	0.04	0.04	0.38	0.34	0.35	89.10
	Acceleration	0.03	0.02	0.02	0.59	0.27	0.41	107.42
	Deceleration	0.04	0.03	0.03	0.41	0.31	0.33	104.61
C3	Hot idle	0.07	0.07	0.14	0.70	0.28	0.45	97.40
	90-kph	0.03	0.02	0.04	0.94	0.24	0.48	106.22
	Start up	0.03	0.03	0.03	0.28	0.12	0.19	95.18
	Stop	0.05	0.06	0.10	0.60	0.35	0.48	92.84
	Acceleration	0.03	0.03	0.03	0.49	0.16	0.33	107.38
	Deceleration	0.02	0.02	0.02	0.59	0.19	0.38	104.41

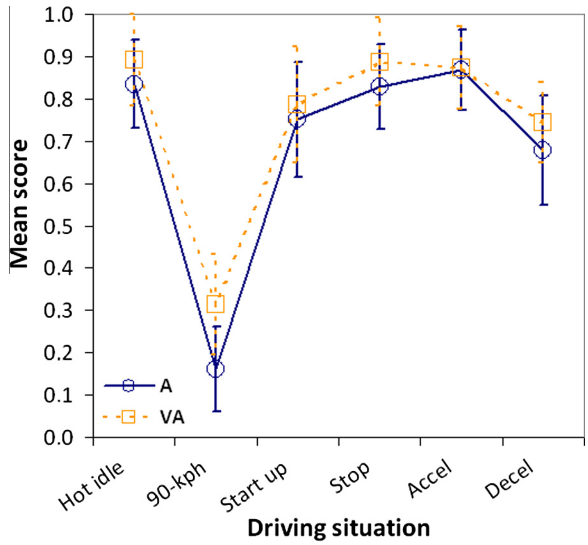

Fig. 7. Dieselness mean scores and standard deviations of six driving situations for acoustics (A: blue round) and vibro-acoustic (VA: orange square) modalities for C1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

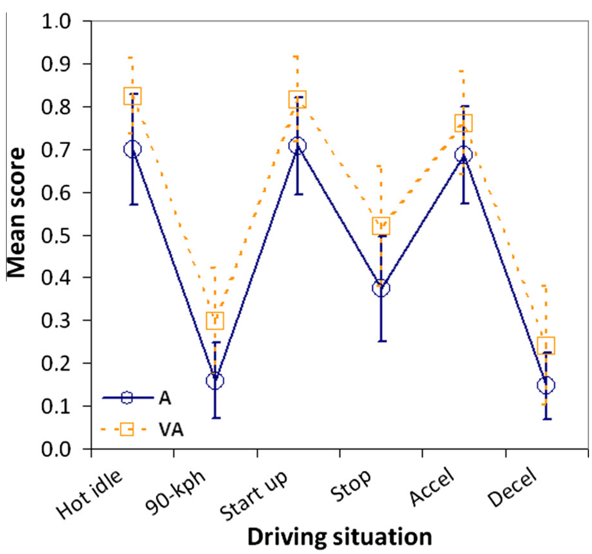

Fig. 8. Dieselness mean scores and standard deviations obtained for C2.

in line (C2) and a 6 cylinders in "V" (C3). For each driving situation, the two modalities, acoustics (A) only and vibro-acoustic (VA), are exposed to participants.

However, we have to notice here that lengths of all stimuli are different. They vary from 2 s for *start up the motor* and *stop the motor* to about 20 s for *acceleration* for instance. Indeed, during measurement on trails, situations like *acceleration* or especially *traffic light start* can last 120 s whereas situations like *start up the motor* or *stop the motor* last only around 3 s. Obviously, we cannot reduce to 3 s (even less than this) *acceleration* or *deceleration* and we cannot extend the shorter ones. Therefore, we segmented the stimuli in different manners: for the steady ones (*hot idle* and *90-kph*), their length is the same (20 s). Concerning unsteady ones, all *start up the motor* and *stop the motor* last 2 s. The differences of length are noticeable for others (*traffic light start*, *acceleration*, *deceleration* and *traffic jam*). Indeed, in accordance with the cylinders' number of the vehicle, we could not obtain exactly the same duration.

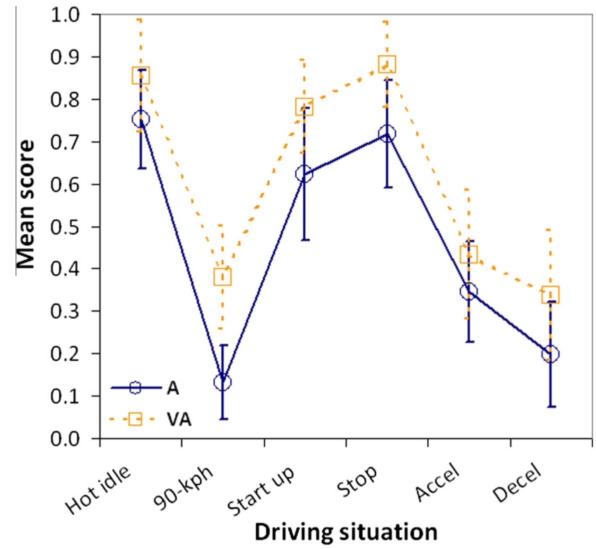

Fig. 9. Dieselness mean scores and standard deviations obtained for C3.

Table 3
ANOVA table with P: French participants, M: modality (A and VA), S: driving situation, V: vehicle (3, 4 or 6 cylinders car), SS: sum of squares, MS: mean square, *F*: *F*-values, *p*: *p*-value, R^2: percentage of total variance accounted for each effect.

Source	df	SS	MS	*F*	*p*	R^2
P	32	10.248	0.320			
M	1	3.100	3.100	44.105	0.0001	2.17
M × P	32	2.249	0.070			
S	5	49.607	9.921	87.558	0.0001	34.67
S × P	160	18.130	0.113			
V	2	9.483	4.741	49.265	0.0001	6.63
V × P	64	6.160	0.096			
M × S	5	0.477	0.095	3.582	0.0043	0.33
M × S × P	160	4.258	0.027			
M × V	2	0.381	0.191	8.874	0.0004	0.27
M × V × P	64	1.375	0.021			
S × V	10	15.481	1.548	31.582	0.0001	10.82
S × V × P	320	15.685	0.049			
M × S × V	10	0.086	0.009	0.436	0.928	0.06
M × S × V × P	320	6.345	0.020			

For instance, the main harmonic of a 4-cylinder car is the 2nd one, whereas it is the 3rd harmonic for a 6-cylinder vehicle. Following the behavior of the proper harmonics from the beginning of recordings (from hot idle around 1000 RPM), stimuli obtained did not exceed about 20 s.

Moreover, Table 2 presents some metrics calculated for each signal measured inside the vehicle: RMS value of acceleration [ms^{-2}] of three directions of seat (s_x, s_y and s_z) and of steering wheel (sw_x, sw_y and sw_z) and sound level L_{dB}.

3.3. Protocol

As precised in Section 1, Dieselness question sums up as: "*Up to what point does this stimulus corresponds to a typical driving situation of a Diesel car?*. The methodology chosen for Dieselness appraisal is a direct estimation on a continuous scale (Fig. 6). Participants evaluate each signal with a cursor. They can move it from 0 ("the stimulus does not evoke a Diesel engine at all") to 1 ("the stimulus evokes a Diesel engine perfectly").

During test, the same instruction is given to participants. They have to put their hands on the same place on the steering wheel (with markers on it) and they have to lay their feet down flat on the platform. At the end of the test, a small interview was carried

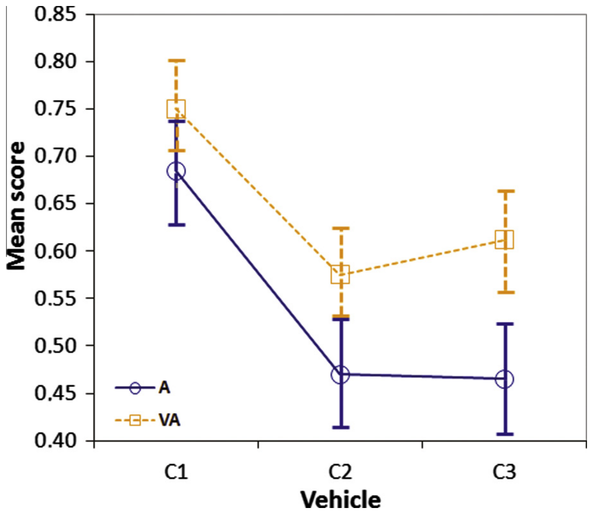

Fig. 10. Variance analysis for the interaction between modality and vehicle for French.

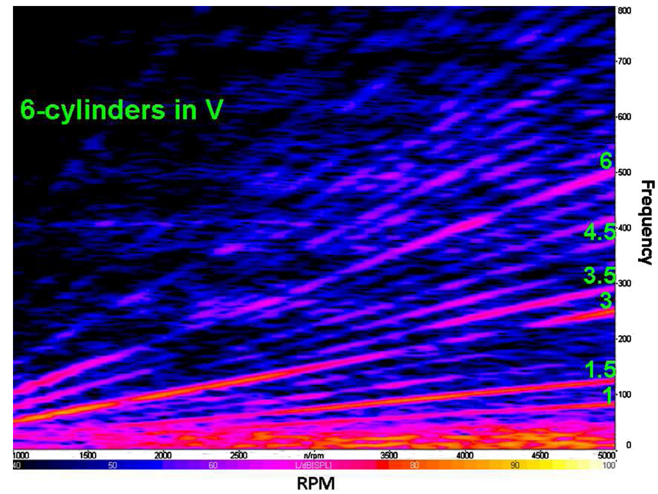

Fig. 12. Acceleration: spectrogram of 6 cylinders car in V.

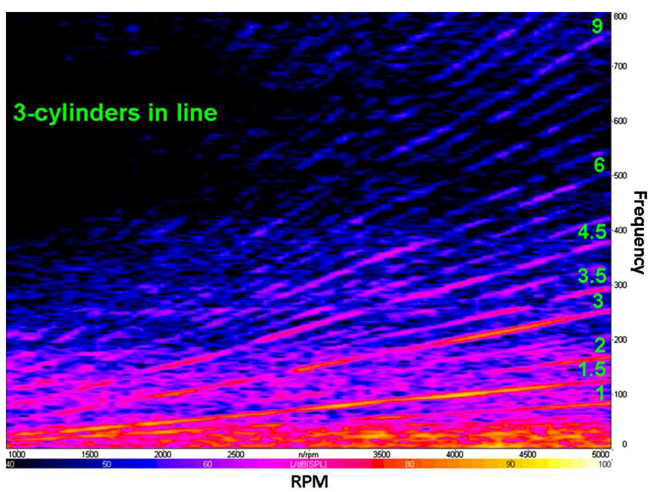

Fig. 11. Acceleration: spectrogram of 3 cylinders car in line.

Table 4
ANOVA table with P: German participants, M: modality (A and VA), S: driving situation, V: vehicle (3, 4 or 6 cylinders car), SS: sum of squares, MS: mean square, *F*: *F*-values, *p*: *p*-value, R^2: percentage of total variance accounted for each effect.

Source	df	SS	MS	*F*	*p*	R^2
P	33	12.222	0.370			
M	1	1.362	1.362	13.003	0.0010	1.16
M × P	33	3.457	0.105			
S	5	32.207	6.441	56.893	0.0001	27.40
S × P	165	18.681	0.113			
V	2	6.508	3.254	39.690	0.0001	5.54
V × P	66	5.411	0.082			
M × S	5	0.347	0.069	2.506	0.0323	0.30
M × S × P	165	4.574	0.028			
M × V	2	0.033	0.017	0.688	0.5061	0.03
M × V × P	66	1.592	0.024			
S × V	10	9.015	0.902	18.129	0.0001	7.67
S × V × P	330	16.410	0.050			
M × S × V	10	0.358	0.036	2.193	0.179	0.30
M × S × V × P	330	5.380	0.016			

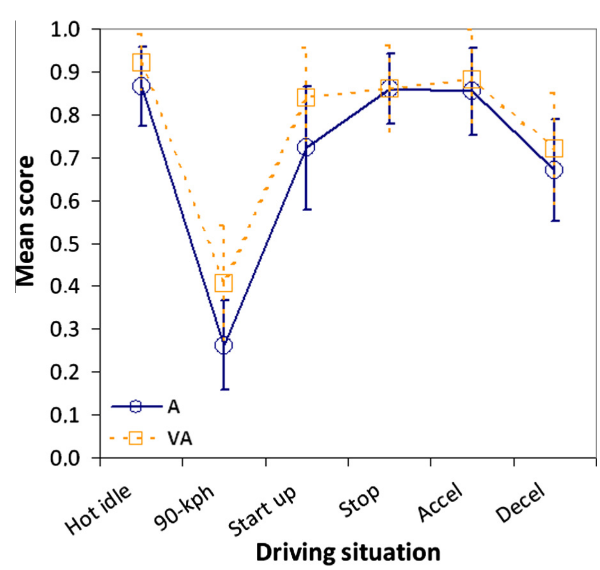

Fig. 13. Dieselness mean scores and standard deviations of six driving situations for acoustics (A: blue round) and vibro-acoustic (VA: orange square) modalities for C1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

out with each person in order to gather their impressions and sensations during the test and to obtain anthropometric data (Table 1). The instruction has been translated in French (for the experiment in France) and in German (for the same experiment in Germany).

4. Results

In the next sections, results for the three main factors – modality, vehicle and driving situation – are presented and discussed, based on a repeated-measures analysis of variance (ANOVA), first for the French participants, and then for the German participants. Finally, results for both populations are compared.

4.1. French participants

4.1.1. Reliability

The first step of analysis is to focus on the reliability of participants' evaluation. Indeed, during Dieselness rating, each stimulus was presented twice in a random order. Calculation of Pearson coefficient is made in order to examine the repetition factor. This coefficient allows to know that 33 participants are reliable in their evaluation. Indeed, the two participants who seem to be not reliable, obtain a correlation coefficient of 0.2 and 0.3. Therefore,

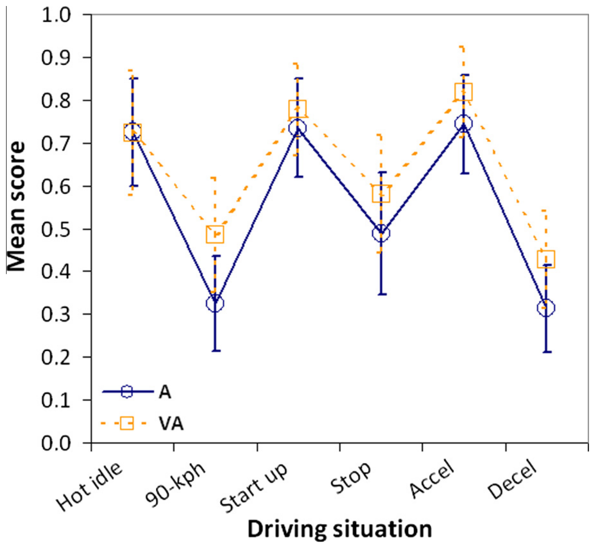

Fig. 14. Dieselness mean scores and standard deviations obtained for C2.

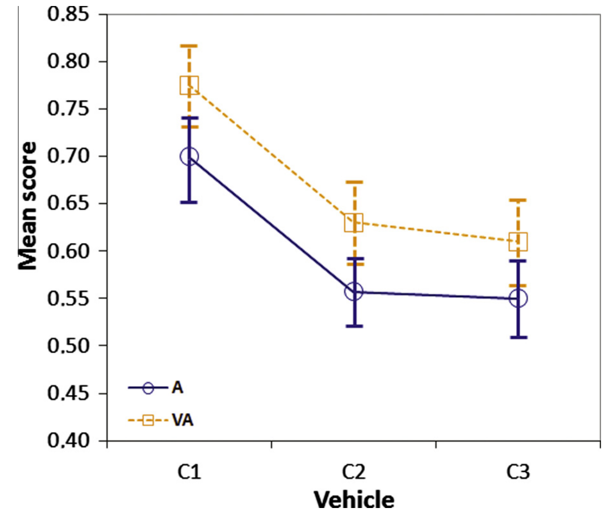

Fig. 16. Variance analysis for the interaction between modality and vehicle for German.

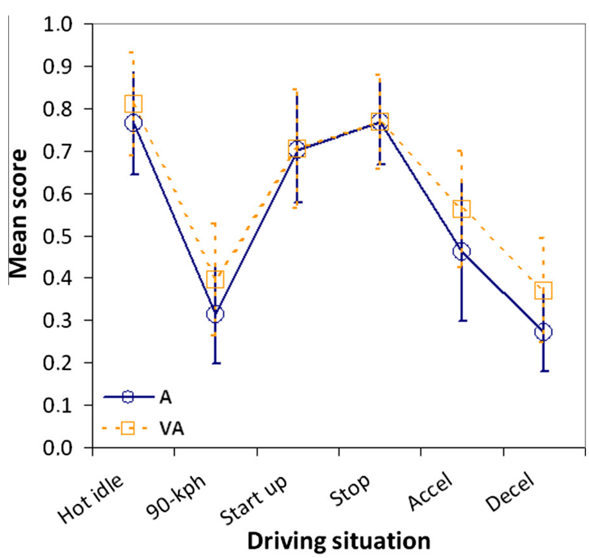

Fig. 15. Dieselness mean scores and standard deviations obtained for C3.

Table 5
ANOVA table with P: group of participants (French and German), M: modality (A and VA), S: driving situation, V: vehicle (3, 4 or 6 cylinders car), SS: sum of squares, MS: mean square, *F*: *F*-values, *p*: *p*-value, R^2: percentage of total variance accounted for each effect.

Source	df	SS	MS	*F*	*p*	R^2
P	1	1.022	1.022	2.958	0.902	0.39
P (Group)	65	22.469	0.346			
M	1	4.299	4.299	48.969	0.0001	1.64
M × P	1	0.189	0.189	2.158	0.1466	0.07
M × P (Group)	65	5.706	0.088			
S	5	80.816	16.163	142.703	0.0001	30.84
S × P	5	1.257	0.251	2.220	0.0520	0.48
S × P (Group)	325	36.811	0.113			
V	2	15.738	7.869	88.415	0.0001	6.01
V × P	2	0.297	0.148	1.667	0.1928	0.11
V × P (Group)	130	11.570	0.089			
M × S	5	0.631	0.126	4.644	0.0004	0.24
M × S × P	5	0.195	0.039	1.435	0.2112	0.07
M × S × P (Group)	325	8.832	0.027			
M × V	2	0.163	0.082	3.577	0.0307	0.06
M × V × P	2	0.256	0.128	5.618	0.0046	0.10
M × V × P (Group)	130	2.967	0.023			
S × V	10	23.549	2.355	47.691	0.0001	8.99
S × V × P	10	1.044	0.104	2.114	0.0216	0.40
S × V × P (Group)	650	32.095	0.049			
M × S × V	10	0.127	0.013	0.701	0.7236	0.05
M × S × V × P	10	0.313	0.031	1.738	0.0689	0.12
M × S × V × P (Group)	650	11.725	0.018			

results presented in following take into account only the 33 participants.

4.1.2. Results

In this section, mean scores of the six driving situations without vibrations (modality A) and with vibrations (modality VA) for all vehicles (3 cylinders car C1 in Fig. 7, 4 cylinders car C2 in Fig. 8 and 6 cylinders car C3 in Fig. 9) are presented and discussed. A score of 0 corresponds to a *stimulus which does not evoke a Diesel engine at all* whereas a score of 1 represents a *stimulus which evokes a Diesel engine perfectly*. Each graph is divided into two parts with two stationary driving situations at the left side (*hot idle* and *90-kph*) and four unstationary ones (from *start up the motor* to *deceleration*) at the right side.

In addition, an ANOVA analysis was performed for three factors (2 Modalities, 3 Vehicles and 6 driving Situations): $P_{33} \times M_2 \times V_3 \times S_6$. The percentage of total variance accounted for by each effect is indicated by the R^2 coefficient. All results of this statistical analysis are presented in Table 3.

4.1.2.1. Influence of the modality. By focusing on the charts (Figs. 7–9), the first observation concerns the fact that VA modality makes driving situations more Diesel than A modality. The variance analysis confirms this observation ($F(1,32) = 44.10$, $p < 0.01$). However, this modality effect depends on the kind of vehicle ($F(2,64) = 8.87$, $p < 0.01$). Indeed, by representing the interaction between modality and vehicle (Fig. 10) which takes into account all driving situations, we can notice that the vibration effect is more important for C2 and C3 than for C1. This difference can be explained by the fact that on the average vibrations on the steering-wheel corresponding to the *x* direction are stronger for C2 and C3 than for C1. Moreover, the modality effect depends on the driving situation factor ($F(5,160) = 3.58$, $p < 0.01$) too. For example, we can notice that for *acceleration* of 3 cylinders car, this situation is felt as Diesel, with and without vibrations with a mean score of 0.87 (cf Fig. 7).

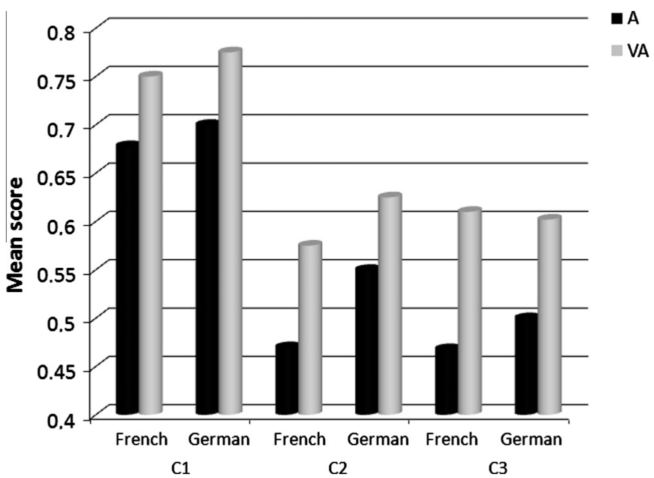

Fig. 17. Mean scores for all driving situations taken together for each car (C1, C2 and C3), for each population (French and German) and for A and VA modalities (respectively in black and gray).

This particular result can be explained by the noise level of this driving situation. Indeed, this is the highest level with $L_{dB} = 110.96$ dB whereas for all other situations, L_{dB} is lower (Table 2). Moreover, since r.m.s. accelerations of seat and steering wheel (s_x, s_y, s_z, sw_x, sw_y, and sw_z in Table 2) are not the strongest for *acceleration*, their effects are reduced compared to those of other situations.

4.1.2.2. Influence of the vehicle. The charts show also different "behaviors" of Dieselness scores for C1, C2 and C3. This is confirmed with a significant effect of the vehicle factor ($F(2,64) = 49.26$, $p < 0.01$). Indeed, by examining the different figures (Figs. 7–9), we can make some remarks. We notice that C1 and C3 obtain mean scores very close for *start up the motor* (respectively 0.79 and 0.78) and *stop the motor* (respectively 0.89 and 0.88), for VA modality. If one refers to Table 2, one can point out that even if sound level of C1 is higher (except for *acceleration* and *deceleration*) than those of C3, the r.m.s. accelerations of steering wheel's appear higher for C3 than for C1. Morioka and Griffin [2] compared in 2008 the perception's thresholds of fore-and-aft, lateral and vertical vibrations by seated persons (at the hand, the foot and the seat). Their results show that perception's threshold at the hands is about 0.04–0.06 ms^{-2} r.m.s. Besides, Table 2 presents metrics higher than this threshold. Therefore, we can suggest that, of course, accelerations play a key role for the Dieselness evaluation of C3. The last observation concerns the steady driving situations *hot idle* and *90-kph* for which a contrast analysis was performed. This analysis reveals that there is no difference between *hot idle* of C1 and C3. We find the same results for *90-kph*. This analysis shows that distinction between 3 cylinders car and 6 cylinders one is not very clear according to certain driving situations. We can bring as other explanation for difficulties to distinguish C1 and C3 that those two vehicles have common odd engine harmonics. Figs. 11 and 12 present spectrograms of accelerations for 3 cylinders car in line and 6 cylinders car in V. We precise on figures, their main odd engine harmonics (in green, above the harmonic that the number describes, at right side). Those two spectrograms show spectral analysis fairly close with more particularly harmonics 1.5 and 3.

4.1.2.3. Influence of the driving situation. The ANOVA analysis confirms its significant effect on Dieselness evaluation with $F(5,160) = 87.55$, $p < 0.01$. Moreover, the calculation of R^2 reveals that this factor has the strongest effect ($R^2 = 34.7$ in Table 3).

If we focus on interactions between driving situation and vehicle for which the effect of interaction is strong ($R^2 = 10.8$), we can conclude that the vehicle's impact on Dieselness assessment depends on the situation. Indeed, Figs. 7–9 show that Dieselness of *90-kph* situation is different from Dieselness of other driving situations for C1, which is not the case for C2 and C3. For those last two vehicles, *90-kph* and *deceleration* are not different anymore. The *deceleration* has the distinction of being little Diesel and even less Diesel than certain stationary situations. Indeed, during this driving situation, the combustion noise (typical of the sound of Diesel) is not involved. By listening to recordings, it is possible to explain the difference between the 3 cylinders car with the two others. *Deceleration* of C1 (3 cylinders) is characterized by the presence of booming noise (as Diesel clatter with low frequencies). It thus differs from *90-kph* which contains high frequency wind noise that hides the typical noise of the Diesel engine. The *deceleration* of the two other vehicles are closer to *90-kph* than others.

4.2. German participants

For this population, the analyses were performed in the same manner as for French results.

4.2.1. Reliability

Calculation of Pearson coefficient shows 34 participants reliable in their evaluation. Indeed, only, one participant obtains a coefficient of 0.3 which does not represent a strong correlation between his two evaluations. Therefore, results presented in following take those 34 participants with reliable evaluations into account.

4.2.2. Results

Following charts present mean scores obtained for German participants. Driving situations (on the abscissa) are presented in the same order as for French results (from stationary to unstationary ones). In addition, an ANOVA analysis was performed for three factors (2 Modalities, 3 Vehicles and 6 driving Situations): $P_{34} \times M_2 \times V_3 \times S_6$. All results of this statistical analysis are presented in Table 4.

4.2.2.1. Influence of the modality. Same conclusions as for French can be deduced here. With vibrations, signals are felt more Diesel than without (Figs. 13–15). Indeed, the variance analysis confirms this observation ($F(1,33) = 13.00$, $p < 0.01$). However, some exceptions appear: *stop the motor* for C1 with 0.86, *hot idle* for C2 with 0.72 and *start up the motor* and *stop the motor* for C3 with 0.70 and 0.77 obtain same main scores for both modalities (A and VA). Indeed, this dependency of driving situation is confirmed by the analysis of variance ($F(5,165) = 2.51$, $p < 0.05$). However, contrary to French results, there is no longer a dependency between modality and vehicle (Fig. 16). The results show less differences between A and VA modalities than for French participants because vibrations reproduced on the steering wheel on the x direction (resp. for the French bench) are stronger than vibrations reproduced on the y direction (resp. for the German bench). In addition, the effect of the modality is practically equivalent for C1, C2 and C3 for the German.

4.2.2.2. Influence of the vehicle. In order to compare vehicles between them, let's refer to Figs. 13–15. Indeed, the charts show an influence of vehicle with different Dieselness scores for C1, C2 and C3 which is confirmed with a significant effect of this factor ($F(2,66) = 39.69$, $p < 0.01$). As for French results, C1 appears as being more Diesel than other vehicles, for both modalities. Concerning the interaction between modality and vehicle, there is little or even no influence on Dieselness appraisal (cf Table 4). The last observation concerns the steady driving situations *hot idle* and *90-kph* for which a contrast analysis was performed. This analysis reveals that there is significant difference between *hot idle* of C1 and C3 ($p < 0.05$) and very significant difference between C1/C3 and C2 ($p < 0.01$). Results obtained *90-kph* are totally not significant.

4.2.2.3. Influence of the driving situation. Concerning the situations, the figures present the differences which exist between them and the ANOVA analysis confirms its significant effect on Dieselness evaluation with $F(5,165) = 56.89$, $p < 0.01$ and with the strongest effect ($R^2 = 27.4$ compared to 1.2 and 5.5 for respectively modality and vehicle factors).

If we focus on interactions between driving situation and vehicle for which the effect of interaction is the strongest ($R^2 = 7.7$), we can conclude that the vehicle's impact on Dieselness assessment depends on the situation for German too. Indeed, Figs. 13–15 show that for C1, Dieselness of *90-kph* situation is different from Dieselness of other driving situations for C1 (but no longer for C2 and C3, as for French participants).

In order to conclude, we can notice that all the effects (modality one by one or interactions between them) are really lower than the French participants' effects.

4.3. Cultural influence on Dieselness assessment

A last ANOVA analysis was performed taking into account the whole participants: $S(P) \times M_2 \times V_3 \times S_6$. Table 5 presents results of this ANOVA analysis.

This analysis shows that the main factors (Modality, Vehicle and Situation) have a significant effect on Dieselness evaluation whereas the participants do not have one. Concerning the interactions which take into account both populations, none of the interaction gives significant results except interactions between modality, vehicle and participants ($M \times V \times P$ in Table 5) with $F(2,130) = 5.62$, $p < 0.01$. Let's see in Fig. 17 in order to focus on this particular interaction.

Fig. 17 presents results for each car C1, C2 and C3 for each group of participants (French at left side and German at right side of each column). Scores are given for the whole driving situations (because $M \times S \times V \times P$ has no significant effect with $F(10,650) = 1.74$, $p > 0.01$). Therefore, each chart's bar shows score for one vehicle, one population and one modality but for the six driving situations. We can conclude that:

- the modality factor has an effect ($F(1,1) = 48.97$, $p < 0.01$). With vibrations, Dieselness scores are higher than without;
- the kind of vehicle has an effect too ($F(2,2) = 88.41$, $p < 0.01$),
- the group of participants has an effect with particularities according to some parameters. Indeed, for C1, French and German evaluate in a same manner A and VA modalities. For C2, they do not agree with Dieselness score but differences between A and VA are similar. Finally, the two populations are distinguished for C3. The big difference concerns stimuli with vibrations (VA modality). Even if they do not assess acoustics stimuli in the same way, Dieselness scores are really close for stimuli with vibrations (respectively for French and German, 0.61 and 0.60).

This last result confirms a previous remark for C3 that noise level plays an important role on Dieselness assessment. The adding of vibrations do not allow to distinguish the populations.

5. Conclusion

This study deals with interaction between acoustics and vibrations concerning the following question: is there any influence of additional vibrations on Dieselness assessment, *i.e.* Diesel engine cars' character? Dieselness of six different driving situations of three various types of Diesel cars was rated by 35 participants during a perceptual vibro-acoustic experiment. This test was performed in France and in Germany. 36 stimuli were assessed on a Dieselness scale. Indeed, participants had to evaluate each stimulus (only sound or sound and vibrations) along a continuous scale from 0 to 1.

Results show similar tendencies for French and German. First of all, vibrations lead to slightly higher evaluations and statistical analyses highlights its influence on Dieselness evaluation but with a weak impact on it. In addition, vibrations' effect depends on different parameters: kind of Diesel cars (3, 4 or 6 cylinders car) and driving situation too. Despite some few differences, French and German totally agree with the fact that *hot idle* is the most Diesel driving situation, whatever the modality and whatever the vehicle [31].

All results have to be taken with caution because we refer to one 3 cylinders, one 4 cylinders and one 6 cylinders car. Therefore, it seemed difficult to generalize for all vehicles of lower, middle and upper classification respectively. This study provides at least an idea of the differences between three types of engines.

Currently, economical and environmental policies urge car manufacturers towards downsizing, *i.e* a reduction of cylinders' number. If we focus on the 3 cylinders car of this experiment, we can notice it is appraised as the most Diesel between three vehicles. Nonetheless, vibrations' contribution is not significant because with sound only, this car is already assessed as a strong Diesel (contrary to the two other vehicles). As, results, the 3-cylinder car is appraised as the most Diesel. It seems to be natural since 3-cylinder engine vibration has complex excitation forces in engine dynamics. Despite those remarks, we have noticed that the 3 and the 6 cylinders ones have been rated in a close manner. However, these similar assessments seem to be done for particular driving situations as *acceleration* for instance. We have deduced that similarity between them can be explained by their close spectral structure and noise level. Besides, this driving situation can appear as exception. By finishing, let's precise that this study has been realized on three particular cars and that all results have to be taken with caution. They may represent particular cases.

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