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MULTIMODAL APPROACH OF VIBRO-ACOUSTIC COMFORT IN VEHICLES: INFLUENCE OF VISUAL CONTEXT

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ABSTRACT
An experiment conducted to study comfort in cars running at low speed is described in this paper. The aim was to evaluate the influence of the visual context on the evaluation of vibro-acoustic comfort. A simulator was used to reproduce the vertical vibrations of the seat, the noise measured at the front passenger's ears and the image of the road as seen by this passenger. Subjects were submitted to stimuli recorded in 8 cars driving on 2 different roads. These stimuli were distributed into 6 tests containing different associations of modalities (vibration only, vibration + sound, vibration + sound + video). The task of the subjects consisted in evaluating the overall comfort of each situation. Results showed a very strong consensus among subjects and vehicles were clearly discriminated. Comfort was highly correlated with the rms level of seat vibration. No correlation could be found with any sound metric even though it appeared that sound could have a significant influence on judgment. The visual modality induced an increase of comfort evaluation and led to a better discrimination of vehicles. But these effects were quite small, which proved that this visual modality can be omitted in such experiments.

INTRODUCTION
When riding in a vehicle, cars passengers are exposed to complex sensory stimuli involving sight, hearing, touch, etc. Their evaluation of the riding comfort is strongly dependent of their perception of this environment. It is agreed that the prediction of passenger's ride quality necessitates the integration of both noise and vibration. Previous research has generally considered one modality at a time [1]. However, some interactions between these senses may exist as the evaluation of one sense never occurs without the presence of the other. Some studies report such interactions; an overview can be found in [2]. It has been observed from [3] that both modalities can contribute equally to comfort until one becomes highly dominant. Then, the overall sensation seems to be dominated by the more annoying or stronger of the two modalities.

Such observations raise the question of interactions between sound, vibration and vision. As a matter of fact, most events in the natural environment that generate sound and vibration are associated to a specific visual context. An experiment designed to study the interaction of the visual modality on the evaluation of others was conducted. The aim was to investigate whether the presentation of the images of the road as seen by the passenger interacts with the evaluation of the vibro-acoustic comfort. Subjects were asked to evaluate the overall comfort of a situation with and without the corresponding visual context. Different modalities were simultaneously presented to subjects: vibration only *(V)*, vibration and sound *(VS)*, vibration sound and vision *(VIS)*.

APPARATUS
The experiment took place in a laboratory with a *50 dB(A)* background noise level at the position of the subject's head and an average reverberation time of *0.1 s*. A simulation bench equipped with a real car seat was used to reproduce vibrations recorded at vehicles seat's tracks. This apparatus was powered by an electromagnetic vibrator *(LDS - V555)* and allowed reproducing vibrations on the vertical axis *(z)* of the seat in a frequency range varying from *4* to

100 Hz. This bench was placed in front of a *2x3 m* screen where videos of the road were displayed. The sound was presented via two loudspeakers and a subwoofer *(GENELEC – 7050A & 8030A)* situated behind a curtain in front of the subjects. The whole system was driven by a computer equipped with a multi-channel sound card *(Creative – 1820m)* and a video projector *(Sony – VPL CX70)*.

Subjects could be placed in a realistic situation representing a car running at low speed, even if it should be noticed that the vibrations were correctly reproduced at the seat's track and not at the interface between the seat and the subject. This means that reproductions did not represent real cars since the effects of different seats were not taken into account.

STIMULI

For the present study, recordings have been performed in *8* new cars including *5* Diesel engines and 3 gasoline ones. Cars were running in *2^nd^* gear at *30 km/h* on two different roads. The first one *(A)* was a scenic road with a rough surface. The second one *(B)* corresponded to a surface change: cars went from a smooth part of the road to an irregular one.

Stimuli included vertical vibrations of the seat, sound recorded at the passenger's ears and images of the road as seen by this passenger. An accelerometer *(PCB – ICP)* was placed vertically on the seat's track *(front right)*. An artificial head *(HMS IV – Head Acoustics)* was placed on the passenger's seat. A high definition digital video camera *(Sony – HDR HC1E)* was placed on the windshield. A multi-channel measurement system *(SQLab – Head Acoustics)* was used to record the acoustic and vibration signals simultaneously. Synchronization with the video camera was done by playing a clock signal with a digital player connected to both systems. Signals were recorded with a *48 kHz* sampling frequency and *24 bits* quantification.

Different processes were applied to signals in order to prepare them for the subjective experiment. Acoustics signals were filtered to compensate the effect of the loudspeakers and restitute the sound as recorded at the subject's ears. Vibration signals were also filtered to compensate the mechanical transfer function of the bench. Images of the road were extracted from the digital video camera and compressed to an intermediate codec to allow edition and real-time processing. *6* seconds samples of each signal were prepared from these recordings.

DESIGN AND PROCEDURE

As mentioned before, subjects were exposed to signals involving *3* kinds of modalities. *3* associations of these modalities were presented: *VIS*, *VS* and *V*. In the *VIS* configuration, the vibration stimuli were presented simultaneously with the sound and the images of the road. In the *VS* configuration, only vibration and sound were submitted to subjects. The *V* one was composed of vibration only.

For each association of modalities, samples measured in the *8* cars on the *2* roads were submitted to subjects into different experiments. This led to a total number of *48* stimuli distributed into *6* tests. That way, for each road, subjects were submitted to *3* tests corresponding to the *VIS*, *VS* and *V* configurations. It should be noticed that for each road, the same video file was used for all vehicles in *VIS* tests, so that any differences in the visual scene that would have helped subjects to recognize a particular car were removed.

Subjects participated to the 6 experiments in different orders. Half of subjects were submitted to a *VIS* test first. For the other half, *VIS* tests were presented at last. Half of subjects also passed a *V* test before a *VS* one. Moreover, the presentation order of the two roads was alternated for half of them. Each test began with *3* practice samples and stimuli were presented *2* times. Each subject evaluated stimuli corresponding to all cars one time before being submitted to repetitions. The presentation order was also determined to ensure that each subject was submitted to a different series. Each stimulus could be repeated as needed.

47 men and *17* women aged from *20* to *56* years acted as volunteers subjects. They were invited to adopt a comfortable seated posture during the experiment, which lasted approximately *45* minutes. They were asked to figure themselves seated in a real car on the passenger seat, with windows closed and the air conditioning system stopped. Their task consisted in evaluating the overall comfort of the presented situations. They answered by placing a cursor on a continuous scale. This scale was linearly graduated with the following labels, to which were assigned numerical values: *"Not comfortable at all" – (0)*, *"Not very comfortable" – (25)*, *"Relatively comfortable" – (50)*, *"Comfortable" – (75)*, and *"Very Comfortable" – (100)*.

RESULTS AND DISCUSSION

An Agglomerative Hierarchical Clustering *(AHC)* analysis of results was performed by using Ward's method on centered and reduced data. No categories of subjects could be found. This observation was confirmed by performing a Principal Component Analysis *(PCA)*. Subjects were grouped on the first axis, which represented *72%* of the total data inertia. Each of the other axes did not represent more than *6%* of this inertia. These results revealed a very strong consensus among subjects. Thus, they were not divided into different groups for later analysis.

In order to provide an overall summary of the effects of the different parameters associated with each stimulus on comfort evaluation, an analysis of variance *(ANOVA)* was computed. It consisted in factorial combinations of *8* vehicles, *2* roads, *3* test types, *2* repetitions, and *3* parameters associated with the presentation order of stimuli: *"First_Road"*, *"VIS_First"* and *"VS_First"*. All of these *3* parameters had only *1* degree of freedom *(DOF)*. *"First_Road"* defined which of the *2* roads was presented first to subjects. *"VIS_First"* defined whether or not subjects were submitted to *VIS* tests before *VS* and *V* ones. *"VS_First"* defined whether or not subjects were submitted to *VS* tests before *VIS* and *V* ones.

It clearly appeared that vehicles caused the great majority of the result variation. At this point it is extremely important to notice that compared to this parameter, the influences of others were secondary. Except for *"Repetition"* and *"VS_First"*, every effect was also significant *(p<5%)*, as well as first order interactions between them.

The *ANOVA* revealed no significant effect of stimuli repetitions. The same conclusion could be drawn by analysing the results of each test condition separately. Repetitions were then considered as supplementary quotations of vehicles.

The discrimination level between vehicles was also examined. A Duncan test was performed on data from all tests and denoted a high level of separation. Vehicles were significantly divided into *6* groups, with a *5%* risk according to Student's law.

Modality effect

Further analyses were conducted to evaluate the influence of different modalities on inter-individual variability, discrimination level, and comfort evaluation.

Firstly, *6 PCA* were computed on normalized data from each tests. The first dimension always represented the main part of the total dispersion (others axes did not exceeded more than *4%* of inertia). This was due to the high degree of consensus among subjects previously observed in the whole experiment. Nevertheless, for both roads, the importance of the first axis slightly decreased from *92%* in *V* tests, to *82%* in *VS* tests, and *81%* in *VIS* ones. Sound induced a slight increase in the inter-individual variability. This observation was confirmed by comparing the total variance in each kind of test. The visual modality did not seem to influence it significantly.

ANOVA were also computed on data from each test. Results were similar to those previously obtained considering all data at once. However, for both roads, Duncan tests showed that *5* vehicles groups were significantly discriminated for *V* tests, *7* for *VS* tests, and *8* for *VIS* tests. This discrimination rise between *V* tests and *VS* ones can be explained by differences in sounds. Nevertheless, this argument cannot be applied to *VIS* tests since images of each road were identical for every vehicle. Then, it can be concluded that the presence of the visual modality induced a better discrimination of vehicles.

Fig. 1 and 2 present the average comfort scores of vehicles on road A and B as a function of modalities. Results are presented with their *95%* confidence intervals. For both roads, *5* vehicles *(V1, V4, V5, V6, V7)* were evaluated between *"Relatively comfortable" – (50)* and

"Comfortable" – (75), whereas the *3* others *(V2, V3, V8)* were considered as *"Not very comfortable" – (25)*.

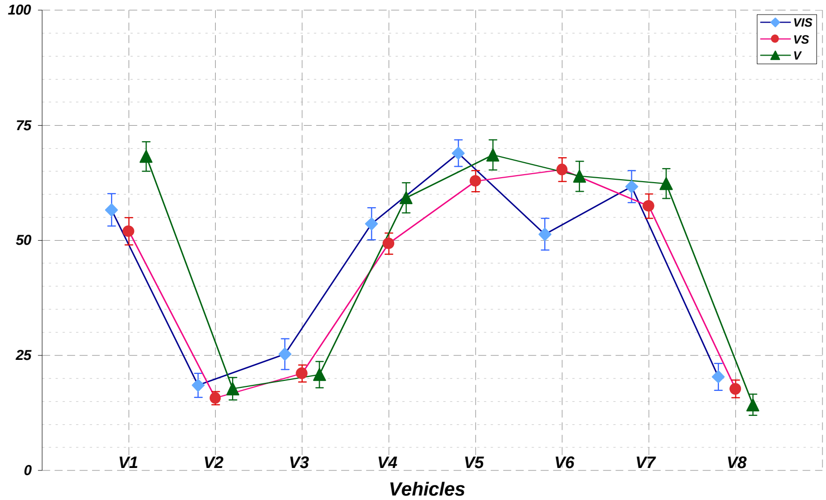

Figure 1.- Influence of modalities on comfort evaluations – Road A

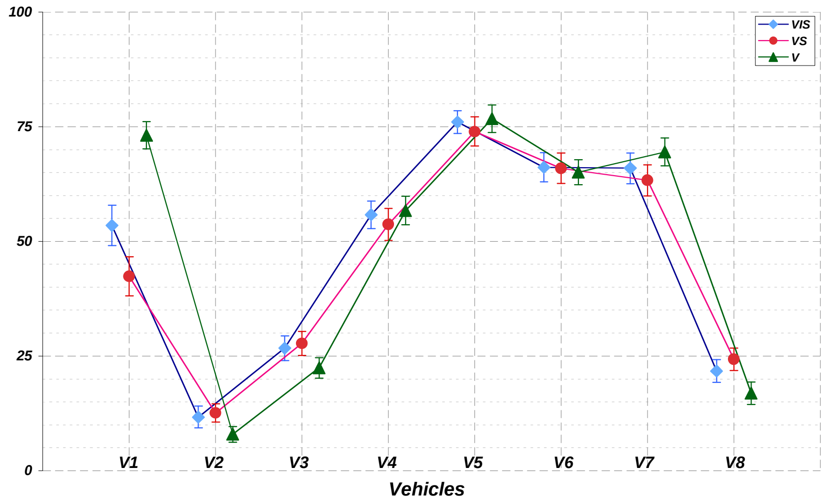

Figure 2.- Influence of modalities on comfort evaluations – Road B

As it was previously mentioned, the modality effects were weak compared to the vehicle one. The *3* curves are very close, which means that subjects were able to evaluate comfort when they were submitted to vibrations only. Nevertheless, the comparison of the *V* curve with the *VS* one shows that the effect of sound varied. No general trend can be observed. However, it should be noticed that sound had an important influence on the evaluation of *V1*: its score went from an average of *70* for *V* tests, to *47* for *VS* tests, and *51* for *VIS* ones. It also appears that, except for *V6*, the *VIS* curve is slightly higher than the *VS* one. The visual modality induced a positive translation in comfort evaluation. But, this effect is very small and negligible compared to the main one.

For both roads, Student tests were performed between data from each test, and showed that they were all significantly different from each other *(p<5%)*. Such tests were also performed on the first order interaction between the two parameters *"Test_type"* and *"Vehicle"*, to determine which vehicles were significantly differentiated according to modalities. Results are summarized in table I. It shows that the different modalities induced significant changes in comfort evaluation for all cars.

Table I.- Significant differences between modalities

	Road A			Road B		
Vehicles	VIS ≠ VS	VIS ≠ V	VS ≠ V	VIS ≠ VS	VIS ≠ V	VS ≠ V
V1	-	+	+	+	+	+
V2	-	-	-	-	+	+
V3	+	-	-	-	+	+
V4	-	-	+	-	-	-
V5	+	-	+	-	-	-
V6	+	+	-	-	-	-
V7	-	-	-	-	-	+
V8	-	+	-	-	+	+

Visual context effect

Effects of the knowledge of the visual context during the evaluation of comfort in *VS* and *V* tests were also examined.

Fig. 3 presents scores obtained in *VS* and *V* tests for subjects submitted to *VIS* tests first and those who were not. As they revealed no significant differences between vehicles, *VIS* curves were omitted for readability reasons. Once more, it appeared that effects were weak compared to vehicles ones. However, except for *V1*, *VS* scores were slightly higher when subjects were submitted to a *VIS* test first.

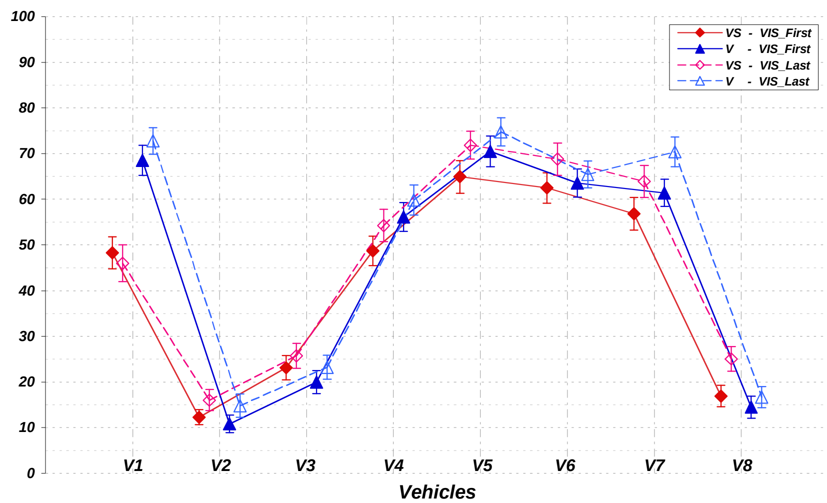

Figure 3.- Influence of visual context on comfort evaluation

The *ANOVA* revealed that the parameter *"VIS_First"* was significant. This means that the familiarity with the visual context influenced evaluations during *VS* and *V* tests. Student tests were performed on data corresponding to the interaction between *"VIS_First"* and *"Test_Type"*. Results of both *VS* and *V* tests were significantly different between subjects who were submitted to a *VIS* test first and those who were not. *VIS* tests results were not influenced by this parameter. Complementary Student tests were also achieved to determine which vehicles were concerned. Results are summarized in table II. It shows that differences were noticeable between *VS* tests for almost all vehicles *(except V1 & V3)*. At the opposite, except for *V2* and *V7*, no significant differences were found between *V* tests.

Table II.- Differences between types of test as a function of *"VIS_First"*

Vehicles	VIS	VS	V	Vehicles	VIS	VS	V
V1	-	-	-	V5	-	+	-
V2	-	+	+	V6	-	+	-
V3	-	-	-	V7	-	+	+
V4	-	+	-	V8	-	+	-

Signals analysis

Physical parameters of stimuli restituted in the laboratory were estimated. Indicators classically found in literature were calculated on vibration signals: level, standard deviation, skewness, kurtosis, vibration dose value *(VDV)*, peak levels, and crest factors. Their definition can be found in [4]. They were calculated from un-weighted and weighted accelerations according to [5]. The following sound metrics were also calculated on acoustic signals: sound pressure levels *(SPL)*, loudness, sharpness, tonality, and roughness. None of these were correlated to comfort. Results showed that comfort score of all tests were only correlated to the rms level of seat vibration *(R=0,95 for VIS, R=0,92 for VS and V)*, and to *VDV*. The use of normalized frequency weightings did not lowered these correlations unlike what has been observed in [6], which means that important frequencies contained in signal were not attenuated.

Acoustic and vibration levels were not correlated. No interaction or summation effect could be estimated since no specific test dedicated to sound evaluation only was performed in this experiment. Moreover, no satisfying model could be found because of the great inhomogeneity of signals characteristics.

CONCLUSIONS

This laboratory experiment of vibro-acoustic comfort evaluation revealed a strong consensus among subjects, combined with a high discrimination level between vehicles. The visual modality induced an augmentation of inter-individual variability and vehicles discrimination. It also produced a slight increase in the comfort scores of most vehicles. The knowledge of the visual context during *VS* and *V* evaluations was also significant. It led to an augmentation of comfort scores. But, all these effects were quite small, which proved that this visual modality can be omitted in such experiment. The overall comfort of the situation was highly correlated with the rms level of seat vibration. It also appeared that sound could have a significant influence on judgments. No satisfying model including both sound and vibration could be found because of a lack of information on sound characteristics. Interactions between sound and vibration could be estimated in further experiments by using modified signals with controlled parameters.

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