Multisensory interaction – A comparative study on driving sound evaluation in moving base and fixed base driving simulators

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Abstract – Perception and evaluation of comfort and quality in a passenger car is strongly influenced by the noise and vibration behaviour of the vehicle and always happens in the context of multiple sensory impressions which are consciously and subconsciously processed in the human brain. The interaction mechanisms of sensory perception are highly complex and raise several scientific questions. In order to investigate the mutual influence of acceleration forces and driving sounds a comparative listening study was conducted in two different driving simulators, one moving base simulator offering longitudinal acceleration forces and one fixed base simulator without motion. During the listening test different vehicle interior sounds and different accelerations were evaluated by 52 non-expert test participants. Afterwards the evaluations from both driving simulators were compared. This comparison didn't bring up any general differences in evaluation between the two different test environments but small effects concerning single items. Based on the results from the study the mutual influence of driving sounds and longitudinal acceleration will be discussed in this contribution.

Key words: *multisensory interaction, sound evaluation, acceleration perception, moving base simulator, fixed base simulator*

1 Introduction

The evaluation of vehicle interior sounds is strongly dependent on the context, in which the sounds are presented [Pau7]. If the results from a listening study shall be assigned to everyday life conditions, the test environment has to reproduce a great degree of reality as well. On the one hand, this means that the test participant has to interact with the vehicle like in everyday life. On the other hand, also non-acoustical sensory stimuli have to be presented during the test in order to take account of the complex interaction processes between multiple sensations that complement one another to form an overall impression of the perceived environment.

The combinations of auditory, visual, haptic, olfactory and somatosensory information being processed consciously and subconsciously by the human brain contribute to judgement formation as well as cognitive processes like attention focusing during a driving scenario and multitasking [Bro3, Kah4]. With these facts in mind, the use of a driving simulator for listening experiments appears to be quite obvious.

The driving simulators used by the vehicle manufacturers become more and more complex and today's computer technology allows real-time simulation of vehicle dynamics and virtual environments with high precision. However, the multitude of sensations and environmental factors affecting a person under everyday driving conditions never can be fully represented in a physically limited driving simulator. Thus the reproduction of realistic driving situations in such a test environment always involves compromises. This raises the question which sensory stimuli are crucial to a high degree of subjectively perceived reality and how these stimuli have to be presented in the driving simulator. Regarding the interaction of visual and auditory perception valuable insights have been obtained during the past years and there are also a number of theories about the auditory-tactile interaction. Perceptual aspects have been investigated in previous studies [Bau1, Mer5] as well as the influence of vibrations on the evaluation of comfort and quality in a vehicle [Bel2, Sko8]. In contrast, the connection between auditory and somatosensory perception remains largely unexplored. Nevertheless, this part of perceptual research is of high importance if a driving simulator shall be used as an appropriate test environment for listening experiments. In the course of this, the question arises how acceleration forces in a moving-base simulator influence the evaluation of vehicle interior sounds. And how do driving sounds affect the sensation and evaluation of longitudinal acceleration? These considerations lead to the more practice oriented question if there is a difference in driving sound evaluation using a moving-base simulator compared with a driving simulator that doesn't offer any motion.

2 Listening study

In order to explore the interaction mechanisms of sound and acceleration perception a comparative listening study was conducted in cooperation with the company Daimler AG using two different driving simulators.

2.1 Test environment

2.1.1 Moving base simulator

The first test environment was the moving base driving simulator owned by the company Daimler AG in Sindelfingen. This simulator consists of a large dome offering space for a full vehicle. In this study a mid-range vehicle was used. The inner wall of the dome is a curved projection screen where the virtual environment is projected onto in 360°. The dome itself is placed on a Stewart platform offering motion in six degrees of freedom. In addition, this construction is flexibly mounted on a guide rail with a movement range of 12 m.

Fig. 1. Moving base simulator (Daimler AG).

The fast linear motors of the electric drive are able to generate translational accelerations up to 1 G. According to the orientation of the vehicle in the dome lateral or longitudinal vehicle dynamics can be simulated with a high degree of realism. The perceived acceleration inside the vehicle is a combination of translation on the guide rail, hexapod movement and pitch. By using different motion cueing algorithms the ratio of translational and rotational movement can be varied. In the course of this listening study the participants should be exposed to inertial forces as strong as possible. Thus a motion cueing algorithm with great amount of translation and moderate pitch was chosen. Since the study was focused on longitudinal acceleration the vehicle in the dome was positioned along the guide rail and moved and pitched forwards and backwards according to the driving manoeuvers. In the course of this, the vehicle dynamics of a mid-range vehicle with automatic transmission was simulated. The driving sounds were presented to the test participants via headphones inside the vehicle.

2.1.2 Fixed base simulator

In the second test environment, a fixed base simulator without any motion cueing, the control group performed the driving test under the same conditions as the treatment group. The test environment was designed equally to the moving base simulator and also the vehicle used in the test was the same. So the only variable to be modified was the “acceleration”. Due to the missing movement the subjective impression of acceleration was just a virtual one.

Fig. 2. Fixed base simulator (Daimler AG).

2.2 Test design

The listening test was subdivided into two parts and took about 45 minutes in total.

In the first part of the test the participants had to drive the vehicle themselves. They had to follow a leading vehicle keeping a distance as constant as possible and imitating the driving manoeuvers of the leading vehicle. The test drive took place on a straight country road during daytime and there were no other traffic participants on the road besides the leading vehicle. Two different driving scenarios each with two accelerations had to be passed. The first scenario consisted of two part-throttle accelerations and the second one of two full-throttle accelerations. Each scenario was presented five times with five different vehicle interior sounds. Thus every test person had to drive ten times in total and carry out an evaluation after each run by filling out a questionnaire. The questionnaire consisted of a 7-step Semantic Differential and the test persons first had to rate the driving sound in terms of the items *Pleasantness, Sportiness, Loudness, Timbre, Powerfulness, Quality.* Beyond that, they were asked to evaluate the vehicle acceleration on the basis of the items *Strength, Realism* and *Familiarity*.

In the second part of the test the driving simulator was set into replay mode and the test persons had to remain passive in the vehicle. Ten short driving scenarios of equal length, which had been recorded previously, were presented one by one to the test persons. The scenarios were composed of three different kinds of acceleration to specified target speeds (80 km/h, 95 km/h, 110 km/h) and three variations of a vehicle interior sound respectively combined with each other. The resulting nine driving scenarios were randomized in order and one scenario was additionally repeated for reliability reasons. After each run the test persons had to carry out their evaluation again using a 7-step Semantic Differential with the items *Sportiness (of the vehicle)*, *Acceleration strength* and *Pleasantness (of the vehicle sound).* In addition, the questionnaire contained questions about the participants' driving experience. The test persons were asked about their annual mileage and the type of vehicle they use regularly.

Before performing the listening test the participants were not informed about the objectives of the experiment. This should avoid a distortion of test results possibly caused by artificial attention focussing. Besides the quantitative evaluation during the test drive narrative interviews were conducted subsequent to the listening test, so the participants could express their impressions and associations concerning the experiment. This kind of explorative evaluation approach gives the opportunity to record the test persons' individual evaluation strategies and frames of reference which can be a valuable addition to the quantitative assessments in the questionnaire [Muc6]. In the course of the interviews the test persons finally were informed about the objectives of the listening study.

2.3 Stimuli

The vehicle interior sounds in the first part of the listening test were five different engine sounds all with the same wind and road noise. In order to cover a wide range of sound characteristics the engine sounds of a diesel vehicle, three gasoline vehicles (sports sedan, mid-range and large executive car) and an artificially designed electric vehicle sound were presented in randomized order.

In the second part of the listening test the interior sound of the mid-range car was presented in three different versions: the original sound and two parameter variations, one of which was a volume increase (+5dB), and the other a level increase in low-frequency range with a cut-off frequency of 280 Hz. The aim of this approach was to investigate if the variation of single sound parameters, e.g. volume, has an effect on the subjective impression of acceleration.

All sounds were generated by a HEAD 3D Sound Simulation System (H3S) and presented to the test persons in randomized order.

2.4 Test participants

52 persons were invited to the listening test and equally distributed by age and gender into a treatment group and a control group. Every test person had to pass the test in only one of both driving simulators (Between Subject Design) in order to avoid learning effects, that would be caused by repetition of the test in the respective other simulator, and to achieve independence between the two experiments. The participants were non-technical employees of the Daimler Company and external persons from the company's test pool aged between 19 and 69 years. The mean age was 38 years with a standard deviation of 13.3 years. 57% of the test persons were male and 43% were female.

3 Results

Subsequent to the listening test the judgements from both driving simulators were evaluated and compared with each other. The results were analysed first with regard to figure out potential differences in evaluation between the two driving simulators and second to investigate mutual effects of vehicle interior sounds and acceleration.

3.1 Sound evaluation

A one-way MANOVA was performed on the sound evaluation results from the first part of the test using Pillai's Trace. There was no statistically significant difference between the ratings from both driving simulators in total ($F = 9.75$, $p = 0.25$, $\alpha = 0.05$). However, additional tests of between-subjects effects revealed a couple of significant differences, so the results were analysed more in detail.

The two most interesting results, the evaluation of the items *Pleasantness* and *Loudness* have been chosen and will be discussed below. Fig. 3 exemplarily depicts the arithmetic means of the item *Pleasantness* in the full-throttle scenario for all five vehicle interior sounds with standard error.

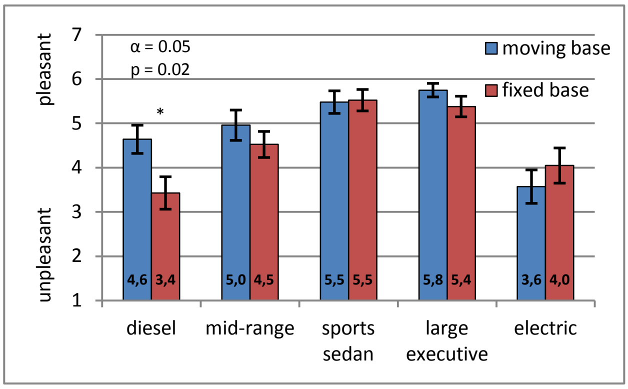

Fig. 3. Ratings of the item *Pleasantness* (full throttle scenario).

A t-test performed on the judgements from both samples on a level of significance of 5% indicates a statistically significant difference in evaluation only for the first sound, the diesel vehicle. This sound obviously was evaluated as more pleasant in the moving base simulator. Concerning the other sounds differences in evaluation are not significant. However, the small number of test participants and the choice of a Between Subject Design decrease the statistical certainty of the test. The coefficient of determination is $R^2 = 0.55$ so that 45% of not explained variance between the samples remains. This can be explained by the composition of the sample or influence factors in the test environment.

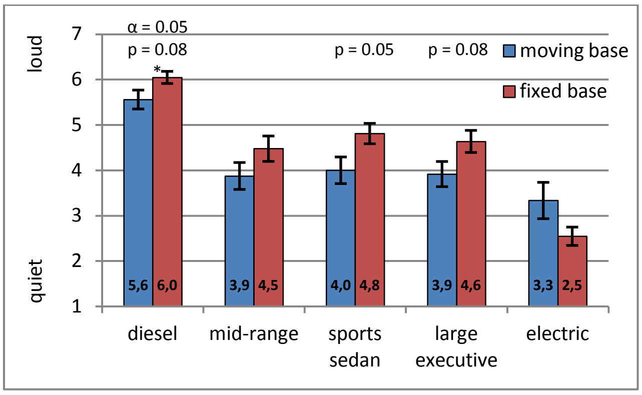

Fig. 4. Ratings of the item *Loudness* (full throttle scenario).

Fig. 4 displays the evaluation of the item *Loudness* in the full-throttle scenario. The arithmetic means are presented with standard error.

There is an offset between the mean values from the moving base simulator compared to those from the fixed base simulator. Although the t-test does not reveal any statistical significance the p-values are close to the significance threshold in three cases. Thus the vehicle sounds in the moving base simulator were evaluated as quieter than in the fixed base simulator.

3.2 Acceleration evaluation

In the next step the influence of vehicle interior sounds on the subjective evaluation of acceleration was investigated. Fig. 5 shows the average judgements of the item *Acceleration strength* in the full-throttle scenario of test part one in the moving base simulator with standard error.

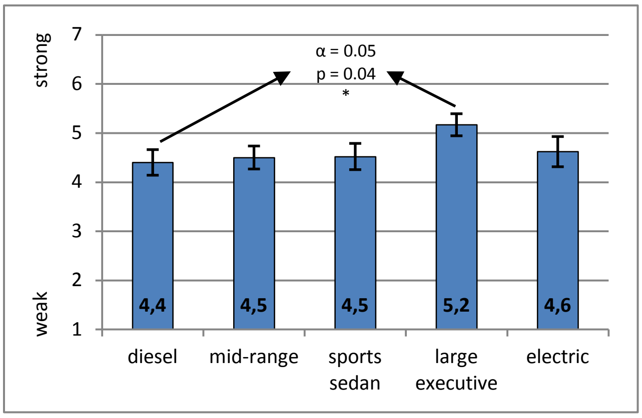

Fig. 5. Ratings of the item *Acceleration strength* (full throttle)

The results show a significant difference in evaluation between the best rated and the worst rated sound. These are the diesel vehicle and the large executive gasoline vehicle. The other sounds were rated similarly.

In Fig. 6 the arithmetic means of the judgements of the item *Acceleration Strength*, now from the second part of the test, are depicted with standard error. The nine different driving scenarios are plotted on the abscissa, labeled by the three target speeds and the corresponding sound variations, where the index *n* represents the normal version, *l* the level variation and *b* the low-frequency variation. The vertical axis shows the seven steps of the Semantic Differential.

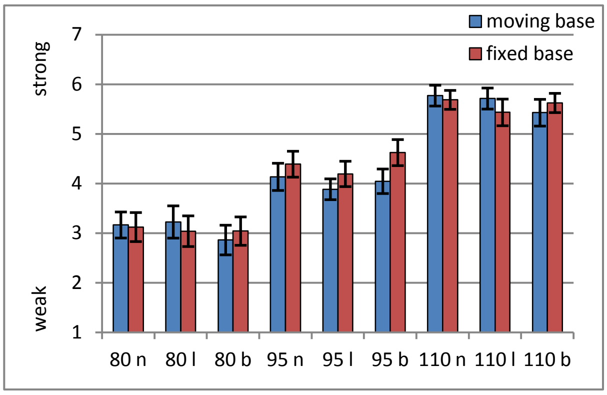

Fig. 6. Ratings of the item *Acceleration strength* (test part II).

The results show no significant difference between the evaluations in the moving base simulator compared to the fixed base simulator. Furthermore, the three sound variations for each acceleration scenario were rated similarly. So there is no influence of the sound variations on the evaluation of the acceleration strength. Only the three different acceleration scenarios were correctly distinguished by the test persons.

In contrast, the judgements on the sound item *Pleasantness* show differences in the evaluation of the three sound variations within one acceleration scenario. The arithmetic means of the ratings are depicted in Fig. 7 with standard error. The labelling of the horizontal axis is the same as in Fig. 6.

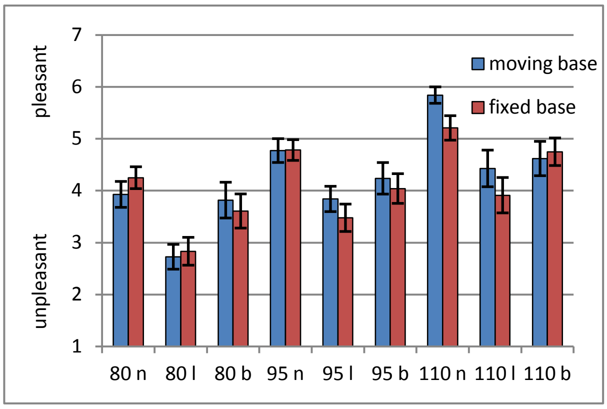

Fig. 7. Ratings of the item *Pleasantness* (test part II)

The volume increase was rated worst in all three acceleration scenarios and also the low-frequency variation has lower mean values than the normal sound. The driving scenarios with the target speed of 110 km/h were rated as more pleasant than the lower accelerations. There is no significant difference in evaluation between moving base and fixed base simulator ($R^2 = 0.86$).

4 Discussion

Concerning single items, the evaluation of the vehicle sounds from the first part of the test conducted in the moving base simulator is slightly different than in the fixed base simulator. There is an offset in the loudness ratings indicating that the vehicle sounds were evaluated as more quiet in the moving base simulator. One possible explanation to this finding is that attention processes in the moving base simulator are different due to the presence of inertial forces as additional stimulus. The test persons might be more deflected from the vehicle sounds because of the superposition of multiple sensory impressions whereas in the fixed base simulator the attention probably is more focused on the sounds when no motion takes place. The item *Pleasantness* among other items also was evaluated differently in both simulators although the differences are very small. Therefore a suggested influence of acceleration on sound evaluation seems to be quiet obvious. It is conspicuous that the electric vehicle was evaluated differently than the other sounds. This finding, together with the fairly wide variety in the results, might be explained by competing frames of reference occurring when test persons evaluate less familiar sounds. The artificial sound character of the electric vehicle has an impact on the test participants' evaluation strategies and also demands more attention from the driver than the well-known sound of a traditional combustion engine.

Although there were only two different driving scenarios in the first part of the test and only the vehicle sounds changed, the evaluation of the acceleration strength in the full-throttle scenario reveals a difference in ratings between the diesel vehicle and the large executive vehicle. These two sound characteristics differ from each other to a large extent. Hearing one of these sounds forms an association with a certain type of vehicle and its acceleration behavior. This means that expectations and prior experiences of the test persons play an important role. These factors apparently have an influence on the subjective estimation of acceleration and the evaluation of the acceleration strength as well.

The test persons' statements in the interviews indicate an interaction of acceleration and sound. For example, many people talked about a stronger impression of acceleration when the vehicle sound gets louder.

However, in the second part of the test the sound variations didn't have any effect on the evaluation of acceleration. Although the test persons clearly distinguished between the different sound variations in the *Pleasantness* rating, the acceleration strength was judged similarly for each target speed scenario. The change of single sound parameters obviously doesn't comprise to a modified acceleration rating. One reason could be the test persons' frame of reference from the first part of the test, where the sound characteristics of the sports sedan, the large executive and the diesel car offer a wider range for the evaluation of *Acceleration Strength* and *Sportiness* than the sound of the mid-sized car with its variations does.

In addition to that, the test persons had several different evaluation strategies except for the auditory stimuli to identify the real differences in acceleration such as the virtual sense of acceleration perceived by the visual system, the real inertial forces sensed in the moving base simulator and the frequency gradient in the vehicle sound. So other perceptual aspects may have been taken into account as indicators for changes in acceleration prior to sound.

Comparing the results from both simulators regarding the second part of the test no significant difference in evaluation could be shown. The coefficients of determination are $R^2 = 0.94$ for the item *Acceleration Strength* and $R^2 = 0.86$ for the item *Pleasantness*. Despite the presence of inertial forces in the moving base simulator both items were not rated differently than in the fixed base simulator.

As a main difference compared with the first part of the listening test, the participants remained passive in the second part and didn't interact with the vehicle. This could explain the different results from both parts of the test.

Moreover, the driving scenarios with the highest target speed (110 km/h) were rated as most pleasant. The coefficient of determination between the items *Pleasantness* and *Sportiness* is $R^2 = 0.55$ and there is a highly significant correlation between the items *Sportiness* and *Acceleration Strength* ($R^2 = 0.96$). The test persons obviously preferred the driving scenario with the highest target speed. This might be associated with particular personality traits of the participants from the company's test pool.

To sum up, the first part of the test indicates small interaction effects between acceleration and sound evaluation although the MANOVA shows no statistically significant difference between both driving simulators. In the second part of the test these effects could not be confirmed. As a consequence, the data from this study reveal no clear empirical evidence of a benefit of using moving base simulators in listening tests. However, the acceleration in the moving base simulator represents only 30% of a real vehicle's acceleration. So the listening study should additionally be conducted in a real vehicle. Furthermore, the role of driving behaviour has to be investigated in detail. Therefore, further research on this topic is of great interest.

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