INFLUENCE OF SYNTHETICALLY VARIED SIGNAL PARAMETERS OF IMPULSIVE VEHICLE SOUNDS ON PERCEIVED QUALITY

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Abstract: A major aspect in the design process of an industrial product is to associate high quality and to evoke customer satisfaction. The product has to fulfill or even to exceed the individual's expectations. Focusing on the general design of common vehicles, all inherent quality criteria contribute to the customer's judgment on perceivable product quality. Therefore, the acoustic characteristics prove as a core criterion for car manufacturers to increasingly strive for a positive impression on the auditory sensation. In this respect, impulsive sounds have a substantial influence on perceived quality since they are the decisive sounds at the first contact inside a dealership [1]. The current study focuses on the influence of signal parameters on perceived sound quality and therefore analyzes synthetic variations of the door locking sound. As an initial step, hearing tests were carried out. The attack and decay time of the main impulse as well as the time properties of a second impulse showed highly significant influence on perceived sound quality. Thus, these signal attributes were synthetically altered and further evaluated in a psychoacoustical experiment using relative and absolute comparison tests [2]. According to this approach, the initial attack time appears as the major influence factor on sound quality followed by the decay time. Moreover, the presence of the second impulse contributes to the listeners's expectation describing the feeling of a securely locked door. The present results enables the vehicle engineer to positively influence the acoustic behavior by optimizing the significant effects of synthetic alterations on perceived quality.

1 Introduction

During the last decade, the technical progress in automotive development led to a high availability of complex technical functions. This process accelerated the paradigm shift from rational to emotional aspects [3]. To further meet the customer's expectations on perceived product quality, the criterion of acoustic appeal became increasingly important [4], [5]. Focusing on the auditory impression, the vehicle itself has to ensure a harmonious and unique character [6], [3] when considering acoustic performance and noise comfort [7]. A major experience concerning emotional sensation will be the real driving condition. Furthermore, the decisive moment for perceived quality of the whole vehicle is the customer's first contact visiting a seller's hall. Based on a silent surrounding without an engine running, the sound quality of functional sounds is highly important for the customer's sensation. As these signals are mainly impulsive and generated by an explicit action of the customer [3], their sound quality appears highly present to the

human auditory system and includes both functional and qualitative information [8], [9], [10]. Since the door unlocking sound represents the first sound perceived when entering a vehicle, it is highly decisive to evoke acoustic appeal and acceptance regarding sound quality [11].
The aim of the present study was to investigate the impact of characteristic signal attributes of door locking sounds on perceived sound quality using synthetic signal alteration. As own previous research [1], [12] indicated, the attack and decay time of the main impulse as well as the time properties of a second impulse had an impact on perceived quality of these sounds. In a first step, original door locking sounds were recorded. These sounds were synthetically altered in the time domain by changing portions of the envelope of attack and decay time and the characteristics of the second impulse (see Fig. 1b). In order to relate these alterations to perceived sound quality, hearing tests were carried out by the method of relative comparison and absolute judgment. This subjective data was correlated to an overall psychoacoustical prediction model previously derived to predict the perceived quality of original door locking sounds [12]. The knowledge of the effect of particular signal attributes on the customer's expectation is of great importance to acoustic engineers to guide them in the acoustic design process.

2 General Methods

2.1 Stimuli and setup

Several door locking sounds from different vehicles have been recorded in a semi anechoic chamber using an artificial head (HEAD acoustics GmbH, type HMS IV) as schematically shown in Fig. 1 a). The recording setup allows to maintaining directional hearing by reproducing main aspects of interaural time and level differences as found in real head [13], [3]. The corpus was placed in a fix position next to the car's b-pillar with the microphones 165 cm over

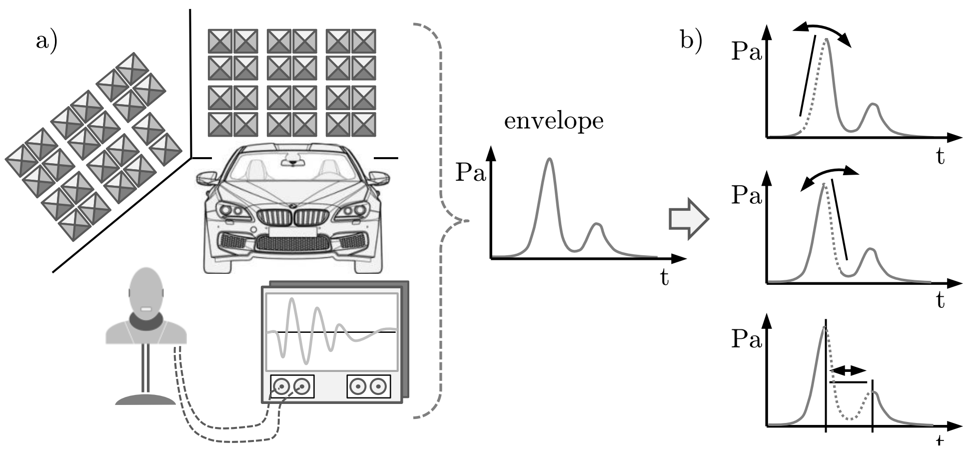

Figure 1 - a) Binaural recording of the sounds in a semi-anechoic chamber and b) synthetic alteration of attack time, decay time and distance between the impulses.

ground. Based on previous quality assessments of door locking sounds [1], [12], four original stimuli were selected reproducing the whole range from high to low quality. Together with the synthetically altered sounds a total of fourteen sounds were used in the experiment. The synthetic alterations are shown schematically in Fig. 1 b).

2.2 Hearing tests

To evaluate the perceived sound quality, the methods of paired comparison and categorical judgment were used [14]. Prior to each experiment, a standardized text explaining both the method applied and the test procedure was handed out to the participants in written form. For a most realistic playback, the sounds were presented over open head phones, type STAX SR-202. In total, sixteen women and 26 men with an average age of 30.2 years participated in the experiments, all of them reporting a normal hearing ability.

Concerning the paired comparison test, the fourteen sounds were divided into two groups of eight with two of the sounds being equal. Based on the restrictive criterion of context independence whilst making a choice [15], two men and two women were excluded from further analysis. They showed inconsistent responsiveness for the χ^2-Test at a confidence level of α=0.05. Combining the eight sounds (28 pairs) by the algorithm of Ross [16], the number of pairs between the first and the next repetition of a stimulus was maximized. Additionally, the elements were presented equally often on first and second position. As the listener's preferred decision was made on the psychological continuum, the information about the actual difference had to be derived from the frequency, she or he favored one sound to another [17]. Thus, the cumulative results have been transformed to an interval scale via dominance matrix [18], [17], [19].

For the method of categorical judgment, the participants were asked to assess the sound quality on a seven-point Likert scale. Based on the opposing adjectives *low quality* and *high quality*, the scaling was further specified in equidistant steps. As the participants had to indicate the perceived quality of each of the fourteen sounds randomly two times within the experiment (test and retest), a statistical check of the consistency of the answers was realized.

2.3 Synthetic Alteration

The *adsr*- envelope model [20] was used with respect to the singular impulsive characteristics of the door locking sounds. The analysis revealed that the amplitude of the sustain time had no significant influence. Thus, the focus was mainly to vary attack and decay time and secondary on release time. As the signals were conceived to be classified via subjective evaluation and objective analysis, no disturbing or deviating noise effects within the sound were accepted. Since the acoustic conditions of door locking show a very fast and impulsive transient process, artificial signal transients have to be considered. Such artificial transients were avoided, if the selected area to alter the sound included a zero-crossing of the curve.

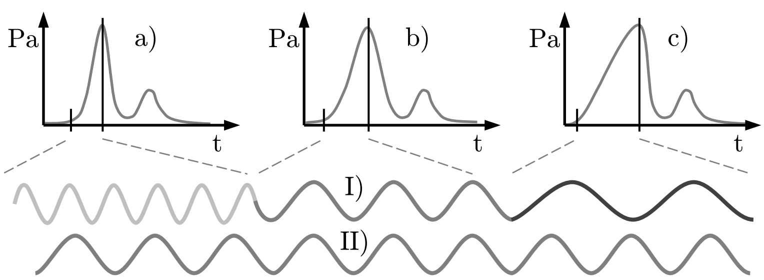

Figure 2 - Pitch shifting: original sound b) compared to bulged a) and alongated c) signal properties including their corresponding changes in frequency.

A second effect to consider depends on the playback speed of the sound and is described by the method of pitch shifting [21], [22]. Based on the relationship between pitch and frequency, bulging and elongation correlate with the inherent frequency characteristics of the sound. For example, a lower playback speed would evoke a significantly deeper perception of pitch than the original signal. In Fig. 2, an original sound b) is shown together with a signal where the first part was bulged a) or elongated c). The lower panels I) show the corresponding changes in frequency. Moreover, the lower panels II) show the signal properties, after the pitch shifting was implemented properly. For the further analysis of the sounds within this study, both acoustic aspects have to be considered.

3 Results

A correlation analysis between the relative and absolute classification showed a significant high value of $r = 0.95$, i.e., the subjective ranking was regarded as valid. For the objective description of perceived sound quality with psychoacoustical parameters, the focus was thus on both a cross-signal and a parameter-oriented analysis.

3.1 Impact of alteration method

Cross-signal analysis

The most significant influence to the perceived sound quality is represented by varying the attack time of the signal. The cumulative results of the paired comparison test are shown in Tab. 1. Stimuli altered in attack time A_a, $B_{a'}$ and C_a were classified best relative to their own corresponding vehicle. Compared to the attack time, the modifications in decay time (A_d, $B_{d'}$ and $C_{d'}$) had less impact on sound quality. Moreover, the synthetic alteration of the distance to the second pulse affected the perceived quality not as much as the other alterations of the door locking sounds. However, short distances to the second impulse as well as the combinations with the steeper attack and decay time evoked an artificial impression of the sound. Thus, these stimuli were ranked last relative to each vehicle ($A_{i'}$, A_{adi}, $D_{i'}$).

Table 1 - Interval-scaled ranking of the cumulative door locking sounds of group 1 and group 2 using the method of Bradley, Terry and Luce [17]. Alteration notification: X_a: attack time, X_d: decay time, X_i: properties of second impulse

ranking	vehicle	scale	ranking	vehicle	scale
1	A_a	0.53	8	C_a	0.32
2	A_d	0.50	9	$C_{a'}$	0.21
3	$B_{a'}$	0.45	10	$C_{d'}$	0.16
4	$B_{d'}$	0.44	11	D_i	0.02
5	A_i	0.42	12	D_a	0.01
6	$A_{i'}$	0.39	13	D_{adi}	0.00
7	A_{adi}	0.37	14	$D_{i'}$	0.00

Parameter-oriented analysis

In respect to the attack time, a flatter gradient provided positive impact on the perceived sound quality. The effect of gradient can be quatified by comparing the signals C_a (flatter gradient) and $C_{a'}$ (steeper gradient); they differed in perceived quality by 0.11 on the interval scale. In-general, the changes of the gradient evoked a major effect (e.g., Fig. 4d). This outcome seems

to be reasonable since several physiolgical studies showed that an impulsive transient process such as the one of the door locking sound is very stimulating for the human auditory system. For a flatter beginning, the listener's auditory sensation is activated slower and thus, the sound is classified as one with a higher quality.
Similar effects can be derived for the synthetic alterations of the decay time since the listeners judged steeper gradients and quicker ending signals to be of poorer quality. An example is given in Fig. 3b). Comparing the signals $B_{a'}$ and $C_{a'}$ where the attack time was steepend with $B_{d'}$ and $C_{d'}$ where the decay time were changed to a steeper gradient showed that the additional steeper decay further decreased sound quality presumably since it was perceived as an unusual strong damping. This strong damping differs from the listener's common experience and therefore, the evaluation of the sound leads to low quality.
An additional aspect of both attack and decay time is shown when comparing signals A_a and A_d with $B_{a'}$ and $B_{d'}$. Based on the initial ranking of the four original sounds, stimulus B was ranked 0.08 better than stimulus A [12]. Within this study, sound A was positively altered to a flatter attack time A_a and to a longer decay time A_d whereas sound B was negatively varied with a steeper gradient in attack ($B_{a'}$) and decay ($B_{a'}$) time. These effects led to a switch in the ranking of the perceived quality and further prove the results presented in Tab. 1.
Concerning the signals A_i and $A_{i'}$ as well as D_i and $D_{i'}$, a longer distance between the main and second impulse evoked higher sound quality. If this duration is chosen too short, masking effects might influence a clear separation of the two impulses. As mentioned by the participants of the hearing tests, the second impulse has significant influence to the subject as this impulse is necessary to know that the door has definitely been locked. By way of example, a combination of a first and second impulse with an appropriate distance is shown in Fig. 3c).

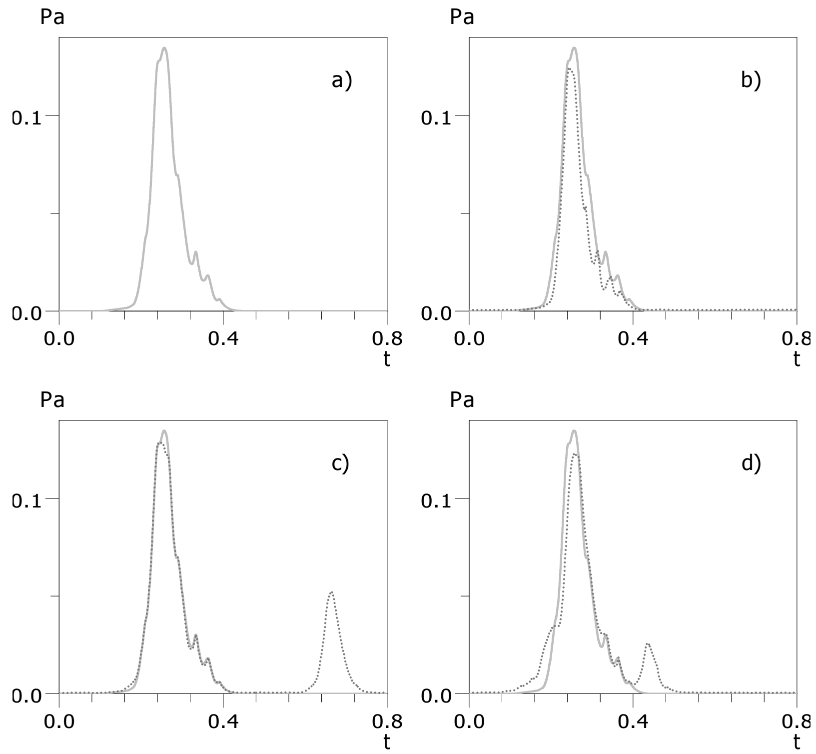

Figure 3 - The envelopes of the Hilbert transformation of serveral signals are shown. a) original sound, b) steeper gradient of decay time, i.e., $B_{d'}$ and $C_{d'}$, c) properties of second impulse, i.e., A_i and $A_{i'}$, D_i and $D_{i'}$, d) flatter attack time, i.e., A_a, C_a, D_a.

3.2 Psychoacoustical model prediction

Based on previous own investigations on original and technically altered door locking sounds [1], [12], a psychoacoustical prediction modelwas developped to impartially describe and predict the perceived sound quality. The model focused on the parameters loudness (DIN 45631/A1) [23] and sharpness (DIN 45692) [24]. Here it is further improved by implementing the data from the current study. In a first step, the psychoacoustical model is derived from original and technically altered vehicles [12]. It has been validated using the results as derived according to Tab. 1. Predicting the perceived quality of the synthetically altered sounds in group 1, a correlation analysis led to a good coefficient of $r = 0.93$. The correlation was $r = 0.90$ for group 2. To further improve the objective prediction of the acoustic property of door locking sounds, the weighting of the decisive model parameters loudness, duration of sharpness [25], [12] and maximal gradient of the main impulse was adjusted. In Fig. 4, the subjective classification of the synthetically altered signals (paired comparison tests group 1 and 2) and the corresponding objective sound quality according to the newly qualified overall model are shown. The high calculated correlation coefficients of $r = 0.92$ and $r = 0.88$ indicate that the predictability of door locking sounds was further improved.

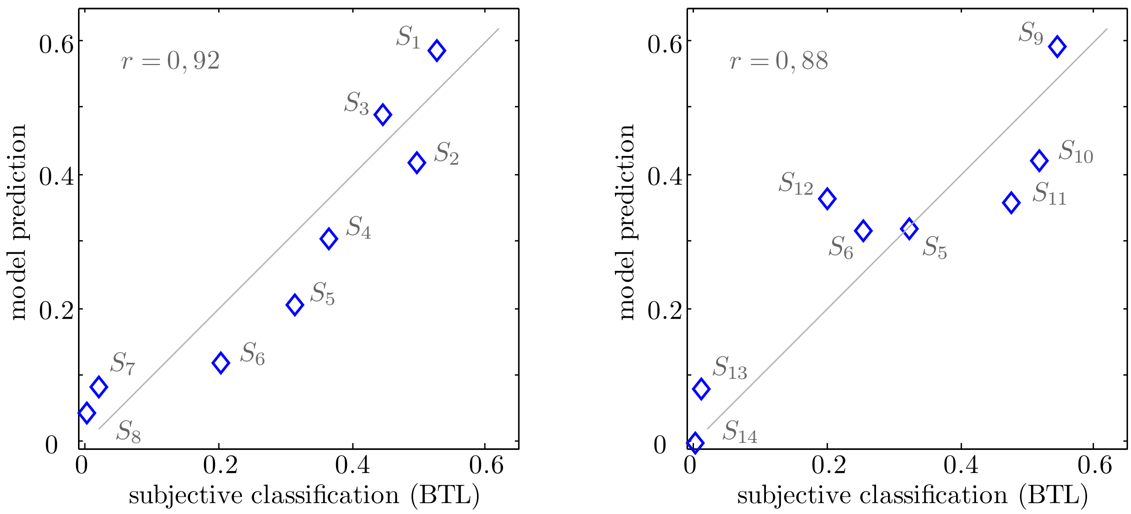

Figure 4 - Comparison of sound quality between subjective classification and objective model prediction. The psychoacoustical model was initially presented in [12].

4 Conclusion and outlook

The present study focused on the impact of characteristic signal attributes of the door locking sounds on the perceived quality. Based on former rinvestigations on original vehicle sounds, the attack and the decay time as well as the duration between the main and second impulse have been investigated in relation to the perceived sound quality. These signal characteristics have been altered synthetically and hearing tests were carried out by the method of relative comparison and absolute judgment to evaluate the perceived quality. Based on the experimental results, the attack time showed a major impact on the auditory sensation. Signals with a flatter

increase of the main impulse evoke a higher value of sound quality. A similar but weaker effect on perceived quality was dshown as the duration of the signal's decay time was alongated. Futhermore, the impact of the second impulse was described important to assure the vehicle has definitely been locked.
Based on the results of this study, the expectation of the customers on the perceived quality can be related to specific aspects of the sound. In the process of sound design, the psychoacoustical model for the door locking sound optimzed here may be used. On the basis of this model predictions testable targets can be derived appropriate for each vehicle category. As a benchmark in sound design resulted to describe and predict the acoustic quality, this offers further potential to perceived vehicle comfort.

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