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Research Article

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Subjective and Objective Evaluation of the Air Conditioning Sound

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Abstract

Nowadays, driver and passenger comfort is a major factor in the automotive industry and sound quality can be seen as one of the most important comfort aspects. In this study, one of the sounds, which can play a role in the customers' perception of vehicle quality – the air conditioning sound – was investigated. In a laboratory experiment, 18 different blower sounds were assessed by 35 participants regarding sound quality, the subjective volume perception, the impression of powerfulness and the impression of hearing a cooling or heating sound. For every sound, the three acoustic parameters A-weighted sound pressure level (dB(A)), loudness and sharpness were analyzed. The results show that high-quality blower sounds are characterized by the fact that they are rather quiet, reserved and powerful. The combination of objective acoustic parameters and subjective assessment show several, more or less strong, connections between subjective and objective aspects of the air conditioning sound.

Keywords: Human factors; Comfort; Air conditioning sound; Sound quality; Perception; Subjective assessments; Objective acoustic parameters; Customer

Introduction

Driver and passenger comfort is a major factor in the automotive industry and one important part of comfort in a vehicle represents sound quality. Sound quality can play an important role in the customer's vehicle selection [1-3]. Furthermore, today, customers ask for more acoustical comfort and pleasant sounds [4,5]. For this reason, the development of high-quality sounds becomes more and more important [6,7] and can nowadays also be seen as an integral part of the brand strategy of many automotive manufacturers [3,8,9].

Nowadays, cars are well isolated from sounds from the outside of the vehicle. Therefore, sounds from the inside of the cabin have more influence on the customer's perception of vehicle quality. One potentially problematic in-cabin sound source is the sound of the air conditioning system. This system has not only a large impact on the well-being of driver and passengers, it can also be a very dominant sound source [1,10,11]. Also, the results of a former research of the Customer Research Center of the Daimler AG show that the air conditioning sound is very important for the customers' impression of the vehicle quality [12]. Also, customers' feedback points out a call for action for this sound. The results of different studies (online as well as with real vehicles) of the Customer Research Center show that most of the German and American participants that assessed the air conditioning sound as unpleasant did this because of the loudness of the sound. Other frequently reported reasons are that the sound does not fit to the brand and/or vehicle and that the sound evokes an impression of poor quality. Too, the results of the company-internal Quality Sensor show in the direction that customers assess the fan/blower as noisy. Even if the loudness of the air conditioning sound seems to be important for the customers' impression of high quality, it must be kept in mind that a powerful cooling and heating of the vehicle is the primary focus of the air conditioning. This aspect can lead to several technical restrictions which made it difficult to implement quiet and pleasant sounds [10,13]. Scheibner and Zeitler [14] postulate based on their research results of various studies on the annoyance of vehicle sounds that the impression of high-quality is supported by the absence of annoying noises. To be more precise, the absence of annoying noise is therefore a necessary condition for a customers' impression of high quality [14,15]. However, it was shown by different research groups that the impression of pleasant vehicle sounds cannot easily be created by only minimizing their sound pressure level. That leads to the recommendation that other acoustic and psychoacoustic parameters like loudness or sharpness should be also taken into account [5,15-18]. Several correlations between the psychoacoustic parameter loudness and subjective discomfort as well as the pleasantness of sounds are reported for noise of various sources [19-22]. Also there are reported relations between the psychoacoustic parameter sharpness and subjective sound perception. A strong characteristic of this parameter is frequently related to discomfort and annoyance [5,19,21,23]. Furthermore, these two parameters are also used successfully in various studies with automotive sounds. For example, sharpness and loudness can be seen in relation with high-quality sounds and pleasantness of engine sounds, interior vehicle sounds and exterior vehicle noises [7,24-26]. Furthermore, based on the experience of the NVH (Noise, Vibration and Harshness) Department of the Daimler AG, the acceptance of functional sounds may depend strongly on three factors: the loudness of the sound, the character of the sound, which can be described with the help of sharpness for a sound like the air conditioning sound, and possible existing interference patterns like e.g. whistling.

There are many sounds that affect the passenger, or the driver, only in a very short span of concentration. As there are warning signals, the turn indicator or sounds from components, switches or doors. In contrast to these sounds, the air conditioning sound affects the car occupants permanently, like the engine sound and wind and rolling sound. Because of the importance of the air conditioning sound, the current study will concentrate only on this aspect of the acoustic

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comfort in passenger cars. This gives us the opportunity for a profound analysis with many different sounds.

The question arises, which characteristics customers assign to a high-quality air conditioning sound. Based on the findings that the inclusion of customers' requirements and emotions is important to develop successful products, subjective assessments and technical specifications should be combined during the product development process [27,28]. This aspect as well as the results of other workgroups described above and the aim to obtain more comprehensive information to improve the air conditioning sound, leads to the decision that beside the sound pressure level, also loudness and sharpness of the air conditioning sounds should be included into the analysis. If there is a connection between the subjective customers' assessments and objective acoustic parameters, the study should help to point that out.

Method

A laboratory experiment was chosen as a method for this study. During the experiment the study participants were sitting in the sound-isolated acoustical cabin of the Customer Research Center of Daimler AG in Boeblingen, Germany. The sounds were presented via headphones (HPS IV, HEAD acoustics).

Sample

In total, 35 untrained participants took part in the laboratory experiment: 26 men and 9 women with normal hearing ability and an average age of 46.88 years (SD=12.62). All participants had a valid driver's license and drove regularly. The exact distribution among the sample can be seen in Table 1.

Materials

In total 18 different blower sounds were assessed by the participants. Each sound sample has a length of 10 seconds. Loops with cross-fade were used for the presented sounds. 14 of the 18 sounds were binaural recordings of original air conditioning sounds (cool and heat) of Mercedes-Benz cars and cars from other manufacturers. The binaural recordings were made using an artificial head (HEAD acoustics). The volume of the 14 sounds has been normalized, which means that the sum level (dB(A)) of the air conditioning sounds were adjusted to a reference sound [51 dB(A)±1dB(A)]. Sound samples which are developed by the filtering of original measurements were not corrected in their loudness, due to avoid manipulation of their spectral impression. The other 4 sounds have been two of the 14 sounds – one sound of an air conditioning that heats (Sound 12) and one of an air conditioning that cools (Sound 15) – with changes in their volumes: in each case louder and quieter than the original sound. To stay close to internal technical requirements, it was decided to use changes of +6dB (Sound 14) and -6dB (Sound 13) for the cooling sound and of +10dB (Sound 11) and -10dB (Sound 10) for the heating sound. This approach should give a first impression to answer the question if the perceived quality of one and the same sound would be assessed differently due to changes in its volume. Figure 1 illustrates the spectra of one representative air conditioning sound to give an example of the sounds which were used in the study. The different air conditioning sounds differ in their pitch, sharpness and tonality, but do not vary regarding their duration and fluctuations.

The questionnaire which was used to assess the different sounds comprised a broad range of items addressing different aspects of customers' opinions about air conditioning sounds. Customer requirements towards the 18 evaluated sounds were operationalized, using 7-point rating scales and items based on semantic differentials, describing different sound attributes (see appendix for details).

Procedure

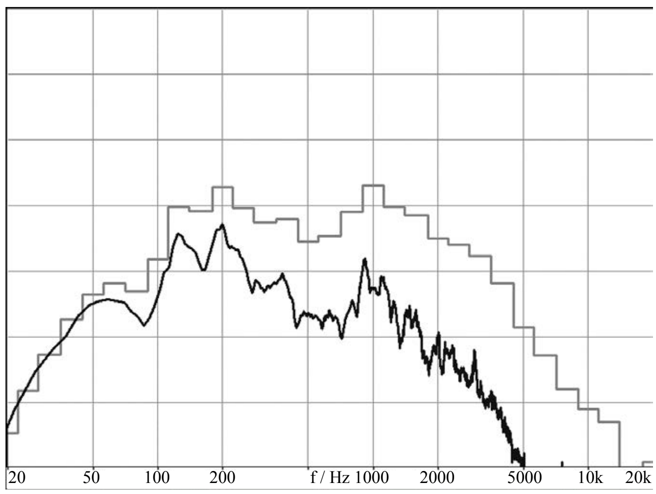
At the beginning of the experiment the procedure was described to the participants. After that, a short interview with questions about their general opinion about vehicle sounds, questions about the sound of the air conditioning in their own vehicle and the appearance of noises was conducted. The next step was the description of the hearing procedure. A within-subject design was used, which means that all participants heard and assessed all 18 sounds in a randomized order. The randomized order of the sounds was chosen to avoid possible sequence effects. Each air conditioning sound was presented with a length of 10 sec. The participants were recommended to listen to the whole sound (10 sec.) before starting the assessment of the sound. If they had problems to assess it after they heard the sound once, they were allowed to hear it again. When the assessment of the sound was finished, the next sound was played and so on and so forth. When the participants finished the assessment of all sounds, a follow-up survey (socio-demographic data) had to be filled out. Every subject needed around 1.5 to 2 hours to complete the whole laboratory experiment.

Sound analysis

The sound analyses for all 18 sounds were conducted using the software ArtemiS. In this study three acoustic parameters were used: A-weighted sound pressure level (dB(A)) and the two psychoacoustic parameters loudness (DIN45631) [29] and sharpness (DIN45692) [30].

Variable		Total
Gender	male	26
	female	9
Age	M	46.88
	Range (SD)	23– 65 (12.62)
Vehicle segment	Luxury and Upper	7
	Middle class	15
	Small and Compact	10
	Others	3

Table 1: Distribution among gender, age and vehicle classes.



Note. black line = averaged FFT, grey line = third octave spectra

Figure 1: Spectra of one representative air conditioning sound.

All parameters represented an average value over ten seconds of a sound signal, the average of left and right ear channel was used.

Statistical analysis

The statistical analyses of the data were conducted using the software SPSS for Windows. Primarily, two scores were calculated: the quality rating score (mean value, semantic differentials not at all/very high-quality, comfortable/pleasant) and the loudness score (mean value, semantic differentials reserved/attention-getting, quiet/loud). Analyses of variance, linear regression analyses and correlations were performed for calculating the results. The analyses were based on a significance level of 5%.

Results

Subjective measures

Subjective assessment: Table 2 gives an overview of the subjective assessments of all 18 air conditioning sounds.

To answer the question if one and the same sound would be assessed differently due to changes in its volume, two analyses of variance with repeated measures, with the mean values of the quality rating score of each sound as dependent variable, were performed. One for the heating sounds and one for the cooling sounds. The results show that there are significant perceived quality differences, because of the volume, for the air conditioning sounds that cools, $F(2,33)=7.276$, $p=0.002$, as well as for the air conditioning sounds that heats, $F(2,33)=12.413$, $p<0.0001$ (see Figures 2 and 3).

Post-Hoc analyses show significant subjective quality differences between the quieter cooling sound (-6dB) and both other cooling sounds (original sound: Sidak, $p=0.022$; louder sound: Sidak, $p=0.001$) as well as significant differences between the louder heating sound (+10dB) and both other heating sounds (original sound: Sidak, $p<0.0001$; quieter sound: Sidak, $p<0.0001$).

Subjective Assessment and quality rating score: A linear regression analysis shows that the loudness score is negatively related ($\beta^*=-0.734$, $p<0.0001$), and the two items “sounds like cool/heat” ($\beta^*=0.153$, $p=0.023$) and “sounds like a powerful air conditioning” ($\beta^*=0.264$, $p=0.002$) are positively related to the quality rating score. These three subjective parameters predict the quality rating score to 95.4% (Adj. $R^2=0.954$; regression equation: *quality rating score*=5.035 - 0.814 * *loudness score* + 0.235 * *sounds like cool/heat* + 0.325 * *sounds like a powerful air conditioning*).

Subjective and objective measures

Quality rating score: In the next step, a linear regression analysis with the three acoustic parameters as regressors and the quality rating score as dependent variable was calculated to show possible connections between them. These linear regression analysis with both parameters for volume - loudness and A-weighted sound pressure level (dB(A)) - shows only one significant β-weight for sharpness ($\beta^*=-0.891$, $p<0.0001$; Adj. $R^2=0.786$). Because of the strong correlation ($r=0.931$, $p<0.0001$) between the two parameters loudness and A-weighted sound pressure level (dB(A)), it was decided to split them and to realize two separate linear regression analyses – one with loudness and sharpness and one with A-weighted sound pressure level (dB(A)) and sharpness as regressors. These two analyses show that all three parameters are negatively related to the quality rating score. For the analysis with loudness ($\beta^*=-0.810$, $p<0.0001$) and sharpness ($\beta^*=-0.788$, $p<0.0001$) an adjusted $R^2=0.777$ is obtained (regression equation: quality rating score=11.537-0.537*loudness-3.950*sharpness). Furthermore, for the analysis with A-weighted sound pressure level (dB(A)) ($\beta^*=-0.891$, $p<0.0001$) and sharpness ($\beta^*=-0.963$, $p<0.0001$) an adjusted $R^2=0.778$ is achieved (regression equation: quality rating score=21.356-0.251*A-weighted sound pressure level (dB(A))-4.830*sharpness).

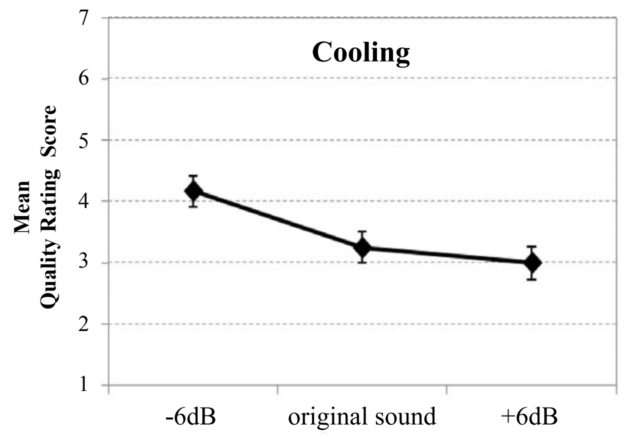
Subjective volume perception: Correlations between the subjective perception of volume and the three acoustic parameters show a strong connection between subjective perception of volume and loudness ($r=0.822$, $p<0.0001$), subjective perception of volume and A-weighted sound pressure level (dB(A)) ($r=0.694$, $p=0.001$) and no significant correlation with sharpness ($r=0.050$, $p=0.845$).

Subjective perception of powerfulness: No significant correlations can be shown between the subjective perception of powerfulness and loudness ($r=-0.100$, $p=0.694$) or A-weighted sound pressure level (dB(A)) ($r=-0.079$, $p=0.755$), but there is a significant connection with the psychoacoustic parameter sharpness ($r=-0.612$, $p=0.007$).

Sound of cooling or heating: Correlations between the impression of the participants to hear a sound of an air conditioner which cools

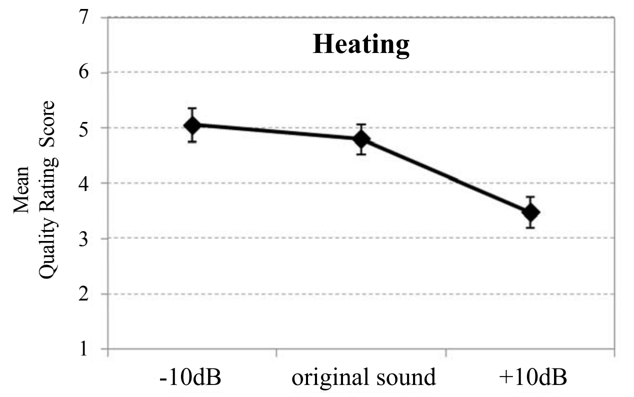
	Quality Rating Score		Loudness Score		Perception of powerfulness		Perception of cooling/heating	
Air conditioning sound	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Sound 1	3.32	1.33	4.60	1.19	4.14	1.38	3.34	1.59
Sound 2	4.34	1.77	4.10	1.57	5.23	1.24	3.79	1.72
Sound 3	4.87	1.65	3.10	1.09	4.32	1.41	3.82	1.70
Sound 4	3.89	1.62	4.41	1.33	4.60	1.68	3.91	1.52
Sound 5	4.12	1.50	4.07	1.32	4.63	1.46	3.94	1.47
Sound 6	3.40	1.48	4.43	1.15	3.80	1.49	3.80	1.43
Sound 7	3.14	1.41	4.86	1.28	3.71	1.58	3.31	1.55
Sound 8	4.19	1.28	3.91	1.25	5.14	1.29	3.77	1.82
Sound 9	3.69	1.57	4.40	1.37	4.14	1.65	2.86	1.35
Sound 10	5.06	1.81	3.13	1.73	4.74	1.56	4.29	1.60
Sound 11	3.47	1.66	5.15	1.29	4.40	2.03	4.49	2.06
Sound 12	4.80	1.59	3.59	1.54	5.34	1.33	4.14	1.80
Sound 13	4.17	1.49	3.89	1.38	4.65	1.70	3.57	1.72
Sound 14	3.00	1.58	4.77	1.32	3.53	1.81	3.29	1.53
Sound 15	3.26	1.46	4.71	1.31	4.14	1.70	3.63	1.57
Sound 16	4.11	1.53	4.16	1.12	4.43	1.60	3.63	1.50
Sound 17	3.64	1.33	4.40	1.33	4.54	1.38	3.23	1.42
Sound 18	4.47	1.44	3.90	1.40	4.76	1.18	3.94	1.75

Table 2: Subjective sound characteristics (Mean values of the subjective assessments).



Note. Error bars reflect Std. Error of Mean

Figure 2: Quality differences due to the volume of the cooling sounds.



Note. Error bars reflect Std. Error of Mean

Figure 3: Quality differences due to the volume of the heating sounds.

(1) or heats (7) and the three acoustic parameters show no significant connection between participants' impressions and loudness (r=0.140, *p*=0.579) and A-weighted sound pressure level (dB(A)) (r=0.212, *p*=0.399), but with sharpness (r=-0.647, *p*=0.004).

Discussion

The first linear regression analysis shows that high-quality air conditioning sounds are characterized by the fact that they are rather quiet, reserved and powerful. The three subjective parameters predict the quality rating score to 95.4%.

The results show that the assumption that the perceived quality of one and the same sound would be assessed different due to changes in its volume can be partly confirmed. The sound quality of the quieter cooling sound was assessed significant better than the sound quality of the original sound as well as the louder cooling sound. Also the sound quality of the louder heating sound was assessed significant worse by the participants than the original sound and the quieter heating sound. These results are in line with the participants' feedback, pointed out of our earlier studies as well as with the results of other working groups, which show several correlations between the loudness of a sound and its pleasantness, as well as subjective discomfort [19-22]. These findings show that from a technical point of view, relatively small loudness changes of an air conditioning sound can have a strong impact on its subjective quality perception. Also they emphasize the importance of the combination of subjective assessments and technical specifications during the product development process [27,28].

The analyses which bring together the subjective assessments and the objective acoustic parameters show that this method can give specific recommendation for action for the acoustic engineering of the air conditioning sound. The linear regression analysis with the acoustic parameters shows that if all three parameters are put in one analysis as regressors, only sharpness is strongly related to the quality rating score. Because of the strong correlation between the two parameters loudness and A-weighted sound pressure level (dB(A)), it was decided to make two separate analyses. These separate linear regression analyses show that all three parameters - sharpness, loudness and A-weighted sound pressure level (dB(A)) - are strongly related to the quality rating score. So, the results suggest that high-quality air conditioning sounds are physically characterized by the fact that they are less pronounced in all three acoustic parameters. This result can be seen in line with the results of other research groups for different sound sources, including every day sounds as well as automotive sounds [5,7,19-26] and confirm the assumption that their conclusions are also valid for the air conditioning sound. So, instead of using only one parameter, the A-weighted sound pressure level (dB(A)), all three parameters should be taken into account for the future sound development process of the air conditioning sound. This is also supported by the results of further analyses between subjective and objective measures. There is no significant correlation between the subjective volume perception and the parameter sharpness, but with the two parameters which are connected with volume. Although both correlations are significant, the parameter loudness results in a higher correlation with the subjective volume perception as the A-weighted sound pressure level (dB(A)). The results show that the participants are able to differentiate volume intensities. Similar results were shown for noises of different sources before [31-33]. The results of the present study show that they retain their validity for air conditioning sounds, too.

We were also interested in the question whether the subjective impression of a powerful sound correlates with one or more of the acoustic parameters. The results show that there is no significant correlation between the subjective impression and the two parameters loudness and A-weighted sound pressure level (dB(A)). In contrast to these results, the significant correlation with the parameter sharpness shows that the less distinct the parameter sharpness for an air conditioning sound is, the more it is a assessed as a powerful sound by the participants. This result supports the conclusion from Fastl [34] that a sound which gives the listener an impression of powerfulness needs to be characterized by the "right" specification of the parameter sharpness.

The question, which of the acoustic parameters gives the participants the impression to hear a sound of an air conditioner that cools or heats can be answered by the result of this study. Only one of the three acoustic parameters used in this study plays an important role: Sharpness. The more distinct the parameter sharpness for an air conditioning sound is, the more the participants have the impression of hearing a cooling sound. The less distinct the parameter sharpness is, the more it sounds like an air conditioning which heats.

Overall, as a sample with 35 participants can be seen as rather small sample, it would be interesting for future studies to examine the correlations found in this study, in a larger sample.

Conclusion

The results of this study show that high-quality blower sounds are characterized by the fact that they are rather quiet, reserved and powerful. Based on the results, the importance of the combination of subjective and objective aspects of a sound for the development of in-vehicle sounds with perceived high-quality, are shown. The interrelation between these two aspects can be an important step to determine further optimization options for the development of high-quality sounds, from a customers' point of view and should be included in future research.

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