Relationship between acoustic perception and overall user experience in vacuum cleaners

Noemi Martin[1], Josephine Lehmann[1], Lisa-Marie Wadle[1]

[1]Fraunhofer Institute for Building Physics IBP, Stuttgart, Germany
(noemi.martin@ibp.fraunhofer.de, josephine.lehmann@ibp.fraunhofer.de, lisa-marie.wadle@ibp.fraunhofer.de)

Abstract

Operating noise from household appliances is increasingly taken into account in buying decisions. This is especially important for vacuum cleaners, as their sound is usually perceived as annoying. The aim of this study was therefore to analyse the operating noise of vacuum cleaners with regard to subjective ratings and to relate it to the overall user experience (UX), as the UX also is an important criterion for the probability of a (re-)purchase.
For this purpose, operating noise of a vacuum cleaner with silence technology and a model without silence technology was recorded in different usage scenarios (variants of flooring and operating modes) and evaluated in a listening test. Furthermore, the UX of the two vacuum cleaner models was evaluated.
The results show that subjective ratings from the listening test depend on both, the usage scenario and the vacuum cleaner model (with or without silence technology). In addition, the results indicate a correlation between acoustic performance and overall UX.
This study shows the potential of human-centered acoustic optimization of vacuum cleaners and the importance of acoustics for overall UX in this application area.

Keywords: user experience, UX, psychoacoustics, vacuum cleaners, household appliances.

1 Introduction

1.1 Theoretical Background

Customers are willing to pay a 14% higher charge for better acoustics from household appliances, as a study by Fraunhofer IBP showed [1]. Yet, the survey of more than 800 participants revealed that vacuum cleaners in German households have a particularly high potential for improvement.
When vacuuming, the user is exposed to operating noise throughout use. Although now there are maximum values for sound pressure levels (SPL) defined [2], noises can be perceived as annoying - for example due to noise characteristics. The operating noises are often annoying and undesirable [1] and can even have a negative impact on the quality of life [3]. The SPL, which has to be declared by the manufacturer, provides information about a physical value, but he customers do not learn anything about sound quality or noisiness of the vacuum cleaner they think about to buy. This is because the SPL does not take into account environmental factors (e.g. context of occurrence of a sound), psychological components (e.g. emergence of stress) or psychoacoustic parameters (e.g. tonality). However, these variables play an important role in the subjective perception of noise quality and annoyance assessment.

Thus, the perception of a sound can vary from person to person [4]. This perception in turn influences the user experience and has an impact on the likelihood of (re)purchase or a recommendation [5].
An additional problem within vacuum cleaners is the perceived link between performance and loudness - customers perceive quieter vacuum cleaners as less powerful while louder vacuum cleaners are perceived as more annoying [6]. This raises the questions of finding the right balance between perception of performance, loudness and annoyance and how the sound quality of vacuum cleaners can be changed to avoid annoyance and still convey high performance to the user.

1.2 Related Studies

Several studies on vacuum cleaner acoustics have been conducted. One of the most important studies for the research questions we tried to answer in our study comes from Altinsoy et al. [7]. In 1999, they developed an annoyance index for floor vacuum cleaners. This involved a test in which participants rated different vacuum cleaner sounds using a semantic differential of nine pairs of adjectives. Results showed that annoyance was influenced by the psychoacoustic parameters loudness (according to Zwicker) and sharpness, among others [7]. In another study, Altinsoy et al. [8] attempted to develop a sound label for household appliances that characterizes the sound quality of products more clearly and beyond SPL.
For both studies, valid sound recordings had to be made and the importance of the microphone position was pointed out. According to Altinsoy et al., the microphone should be where the user would be located, if possible. Moreover, it is recommended that measurements are made with an artificial head. Furthermore, recordings should be made in realistic environments and recorded aurally correct [8]. For this reason, we developed a new measurement setup following Altinsoy and colleagues recommendations (which is untypical in terms of the related EU regulation [2]) to create the recordings for the listening test of our study. The implementation and setup is described in the methods section.
Another relevant study in this context is presented by Kunio et al. [9]. They studied the sound emission of two gearboxes: an established model and a prototype. Although the prototype had a 3 dB(A) lower sound pressure level, its loudness was 8 sones higher according to Zwicker. In addition, its sound was rated as more unpleasant in the listening test. Therefore, sound pressure level and subjective perception did not match [9]. Nevertheless, the current EU regulation restricts vacuum cleaners only in terms of sound level [2].
A further issue that has received sparse attention in this context is the influence of acoustics on the UX. UX is a concept that is most popular in software development, but is increasingly applied to hardware as well. According to ISO 9241-210 [10], user experience is defined as the perceptions and reactions of a user before, during and after using a product. These perceptions and reactions should be as positive as possible, so that the user likes to continue using the product or recommends it to others. Different UX questionnaires are used to measure this concept. A questionnaire that is suitable for the UX of household appliances is the recently developed UEQ+ from 2019, which is a modular extension of the established UEQ (User Experience Questionnaire) [11]. It allows to compose a questionnaire from 16 UX aspects that fits the product under consideration [12]. The UEQ+ is used in the present study to investigate a possible connection between the acoustics of vacuum cleaners and their UX. The role of acoustics within the overall UX is also investigated in this study. Therefore, the study is based on the following hypotheses:

1. Vacuum cleaner models with higher and lower SPLs differ in terms of perceived acoustic parameters (loudness, annoyance, perceived performance).
2. There is a positive correlation between loudness and annoyance.
3. There is a positive correlation between loudness and perceived performance.
4. There is a positive correlation between perceived performance and annoyance.
5. Vacuum cleaner models with higher and lower SPL differ in terms of their UX.
6. The scales of the UEQ+ differed with respect to their perceived importance.

2 Methods

2.1 Recordings

In the first step two suitable vacuum cleaner models were identified. They differed mainly in their SPL. One of the vacuum cleaners was equipped with a so-called “silence technology” and was representative of models with lower SPL. The characteristics of the two vacuum cleaners are presented in Table 1.

Table 1 – Summary of the characteristics of the two vacuum cleaner models.

Characteristics	Model 1	Model 2
Dimensions [mm]	265 x 295 x 410	240 x 307 x 465
Weight [kg]	6,5	7,1
SPL [dB]	75	70
Rated Input Power (2010/30/EC) [watt]	600	850
Silence Technology	no	yes

All recordings were generated using the Squadriga II Head Acoustics headset microphone, which is worn on the head during the vacuuming process and produces realistic binaural noise recordings. The recordings were made in accordance with procedure described in EU Regulation No. 666/2013 [2]. Therefore, the suction nozzle was moved back and forth one-handed in five steady moves for all recordings. Nothing was vacuumed up, as the bags should contain a filling of 400 gram of dust at all times (which were filled in before recordings started), as prescribed in the standard. For both test models, recordings were produced on tiles, laminate and carpet and at three operating states (1 = low, 2 = medium, 3 = high). The floor coverings were selected according to the study by Rukat at al. [13]. All scenarios were recorded in a laboratory where acoustic conditions are comparable to those in an apartment or living room (reverberation time T_{20}=0.45s).

2.2 Test Procedure

All participants were tested in individual test sessions (according to Covid-19 regulations). The tests consisted of two parts: A UX test and a listening test. All participants first performed the UX test in order to prevent priming to the vacuum cleaner sounds before UX testing. After the UX test, the listening test was conducted and demographic data was collected. A total of 40 participants (mainly students) with an average age of M=25.8 years (SD=3.48) participated in the study. 24 were female and 16 were male. Participants were paid for their participation.

2.2.1 UX Test

The UX test was operationalized as a between-subjects design. Each participant did the UX test for one of the two vacuum cleaner models, so each model was tested by 20 participants. During testing, participants were given the task of vacuuming up 8 gram of confetti from a 2.16 m² floor area until it was clean. The surface consisted of tiles, laminate and carpet in equal parts (see Figure 1) to test different flooring conditions. Furthermore, the participants were asked to use the operating states 1 (low power), 2 (medium power) and 3 (high power) at least once during the task.

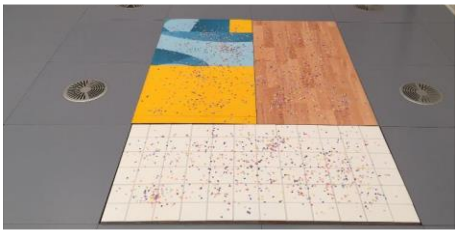

Figure 1: Experimental setup of the UX test

To keep the task as close to reality as possible, it included a complete vacuuming workflow (e.g. picking up and plugging in the vacuum cleaner). The suction bag was already filled with 400 gram of dust. In addition, the lighting in the laboratory was set to match living room lighting. After the participants had tried out the vacuum cleaner, the evaluation took place. It was carried out with the UEQ+ questionnaire (German language). It consists of 16 individual scales that can be used to evaluate various product properties (e.g. acoustics). The respective property is evaluated via four items, which are structured as a 7-step semantic differential. Subsequently, the importance of the evaluated property (with regard to the tested product) was queried (see Figure 2).

Die beim Betrieb des Produkts entstehenden Geräusche sind … (The sounds that are arising when operating the product are …)								
laut (loud)	○	○	○	○	○	○	○	leise (silent)
missklingend (dissonant)	○	○	○	○	○	○	○	wohlklingend (well-sounding)
dröhnend (booming)	○	○	○	○	○	○	○	gedämpft (damped)
schrill (acute)	○	○	○	○	○	○	○	sanft (soft)
Die durch diese Begriffe beschriebene Produkteigenschaft ist für mich … (The product characteristic described by the terms above is … to me)								
völlig unwichtig (completely unimportant)	○	○	○	○	○	○	○	sehr wichtig (very important)

Figure 2: Example of the UEQ+ (acoustics scale)

In the present experiment, the five recommended scales for household appliances were used to evaluate the UX. These are efficiency, acoustics, haptics, usefulness, and intuitive use [14]. The questionnaire was presented via Limesurvey (online-tool).

2.2.2 Listening Test

The listening test was based on the specifications of ISO 16836:2006 [15]. A 2x3x3 within-subjects design was applied. The factors model (2-level), floor (3-level) and operating state (3-level) were varied. All 18 sounds had been recorded and prepared in advance (see 2.1). They were played back aurally correct in the listening test with the Head Acoustics Software SQuare via dynamic, open headphones (HD 600 Sennheiser) and evaluated via tablet. The Head Acoustics PEQ V monitoring station was used for digital equalization and amplification.
All sounds were evaluated on an 11-point scale from 0 to 10, based on the three semantic differentials loudness, annoyance and performance. These rating criteria were selected following the ISO 16832 standard [15] and some related studies [7,16–18]. All participants were familiarized with the tablet and the software through five practice trials. They could listen to all sounds as many times as they wanted. After the sound assessment, some demographic data (gender, age and experience with acoustics) was queried via tablet PC. Hearing ability and noise sensitivity were assessed via subjective evaluation in addition.

3 Results

3.1 UX Test

The UEQ+ ratings were analysed with Excel. Statistical analysis was done using IBM SPSS Statistics software. A significance level of α=0.05 was assumed for inferential statistical calculations. The results for the subjective evaluation of the vacuum cleaner properties are shown in Figure 3 for both vacuum cleaner models. Furthermore, the results for the subjective importance of these properties in the both vacuum cleaner models are shown in Figure 4.

3.1.1 Property Rating

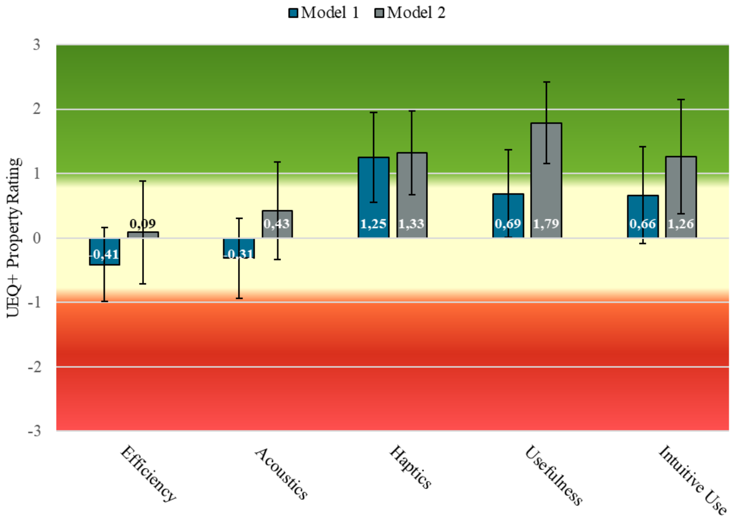

Figure 3: Rating of the 5 properties for both vacuum cleaner models in the UEQ+. Bars indicate mean values. Values between -0.8 and 0.8 represent a neural evaluation of the corresponding scale, values > 0,8 represent a positive evaluation and values < -0,8 represent a negative evaluation. The range of the scale is between -3 (horribly bad) and +3 (extremely good). Standard deviation is shown in addition.

Looking at the results of model 1 (blue bars, Figure 3) the ANOVA reveals statistically significant differences in the evaluation of acoustics and haptics (F(1, 19)=39.09; p<.000; η^2_p=0.64), acoustics and usefulness (F(1, 19)=8.09; p=.01; $\eta^2 p$=0.3) and acoustics and intuitive use (F(1, 19)=5.51; p=.03; $\eta^2 p$=0.23). Acoustics is rated significant worse than the other three properties. There was no statistically significant difference between acoustics and efficiency (F(1, 19)=0.14; p=.72; η^2_p=0.01). Both properties get only poor ratings in model 1.

In model 2 (grey bars, Figure 3), acoustics is also rated statistically significantly worse than haptics (F(1, 19)=10. 2; p=.005; η^2_p=0.35), usefulness (F(1, 19)=17.83; p<.000; η^2_p=0.48), and intuitive use (F(1, 19)=5.01; p=.04; η^2_p=0.21). There is also no statistically significant difference between acoustics and efficiency (F(1, 19)=1.09; p=.31; η^2_p=0.05). Thus, as in model 1, the efficiency of model 2 and the acoustics are rated worst.

3.1.2 Importance of Properties

The differences (bonferroni corrected pairwise comparisons) in perceived importance of the evaluated properties for model 1 (blue bars, Figure 4) show that acoustics is not rated as statistically significantly less important than haptics (z=0.05, p=.92) or usefulness (z=-0.95, p=.06). However, it is rated as statistically

significantly less important than intuitive use (*z*=-1.00, *p*=.05) or efficiency (*z*=2.1, *p*<.000). This is not the case for model 2 (grey bars, Figure 4), where acoustics is statistically significantly more important than haptics (z=1.58; p=.002) and equally important as efficiency (*z*=0.025; *p*=.96), usefulness (*z*=-0.15; *p*=.76), and intuitive use (*z*=-0.40; *p*=.42). Nevertheless, the scales of the UEQ+ are partly perceived as differently important in both models what is in line with hypothesis 6.
Figure 4 shows that both efficiency and acoustics are perceived as important in model 2. However, these parameters get a bad rating (see Figure 3), so there would still be a lot of potential for improvement for these properties.

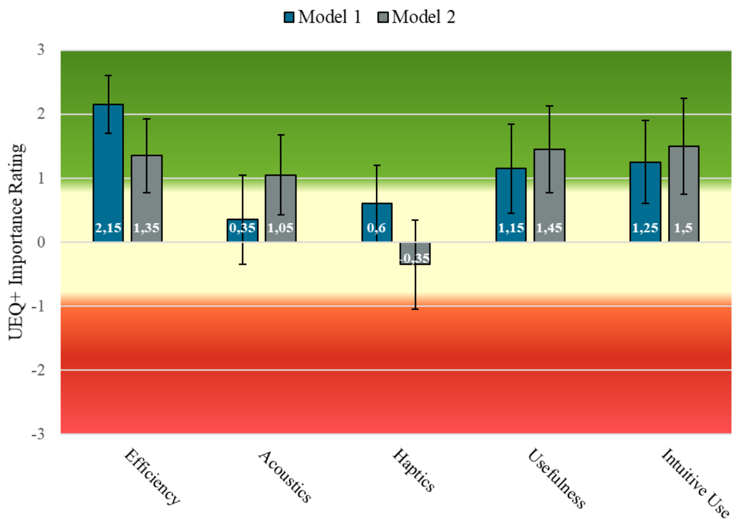

Figure 4: Importance rating for the 5 properties for both vacuum cleaner models in the UEQ+. Bars indicate mean values between -0.8 and 0.8 represent a neural evaluation of the importance of the corresponding item, values > 0,8 represent a high importance and values < -0,8 represent a low importance. The range of the scale is between -3 (not important at all) and +3 (very important). Standard deviation is shown in addition.

3.1.3 Overall UX Rating

The calculated overall UX Rating of model 1 is *M* = 0.33 (*SD* = 0.68) whereas model 2 achieves a value of *M* = 0.95 (*SD* = 0.94). Therefore the overall UX rating of both models lies in the medium range, but the rating of model 1 is still significantly lower than that of model 2 (*t*(38)=2.31; *p*=.03; *d*=0.73), which was assumed in hypothesis 5. The property Acoustics in model 2 with the "silence technology" is also rated low (*M*=0.43, *SD*=1.34), but statistically significantly better compared to model 1 (*M*=-0.31, *SD*=0.87) which had no "silence technology".

3.2 Listening Test

The following data was analysed using IBM SPSS Statistics software. A significance level of α=0.05 was assumed for inferential statistical calculations. T-tests and ANOVAs with repeated measurements were calculated. The two models were compared in terms of their perceived loudness, perceived annoyance, and perceived performance. Additionally, the correlations between these psychoacoustic parameters were considered.

3.2.1 Perceived Loudness

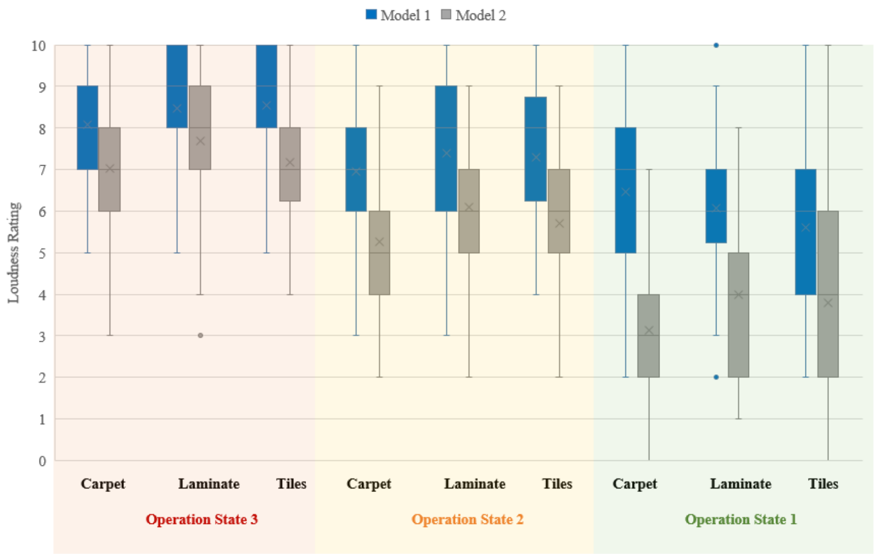

Figure 5: The boxplots show the perceived loudness of both vacuum cleaner models for different operating states and different flooring. The range of the scale is between 0 (very quiet) and 10 (very loud).

ANOVA shows a statistically significant difference between the two vacuum cleaner models in terms of their loudness ($F(1, 30)=162.17$; $p<.000$; $\eta^2p=0.84$). Model 2 (with “silence technology”) is perceived as significantly less loud than model 1 for all operation states and flooring (see Figure 5).

3.2.2 Perceived Annoyance

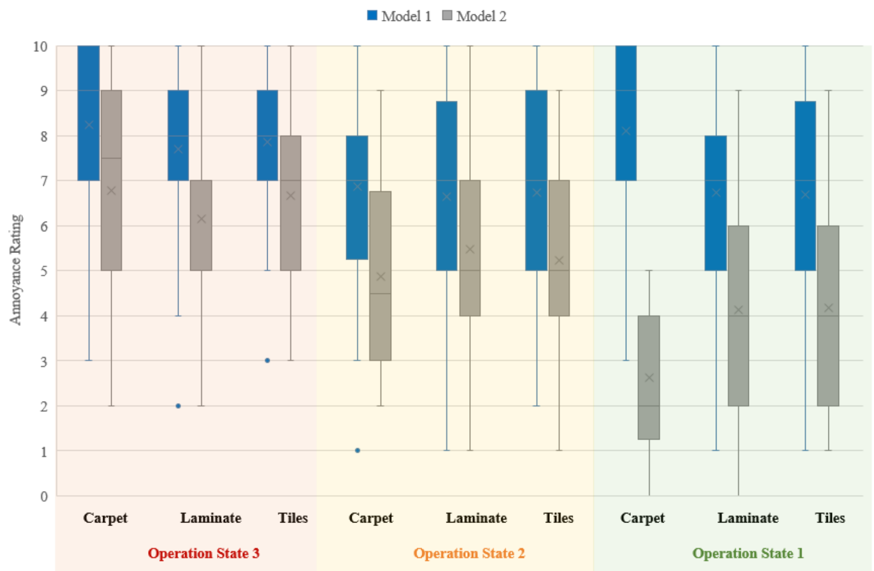

Figure 6: The boxplots show the perceived annoyance of both vacuum cleaner models for different operating states and different flooring. The range of the scale is between 0 (not annoying at all) and 10 (very annoying).

The two models also differ in their annoyance ($F(1, 37)=168.80$; $p<.000$; $\eta^2p=0.82$), model 2 (with “silence technology”) is perceived as significantly less annoying for all operation states and flooring (see Figure 6).

3.2.3 Perceived Performance

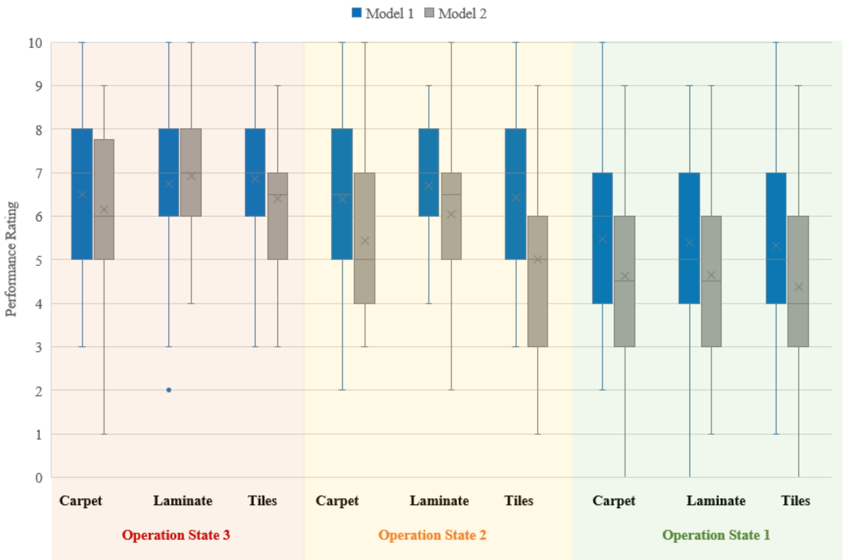

Figure 7: The boxplots show the perceived performance (according to operation sound) of both vacuum cleaner models for different operating states and different flooring. The range of the scale is between 0 (under-performing) and 10 (powerful).

The results for the perceived performance are comparable to those for loudness and annoyance. The performance is perceived as lower for model 2 than for model 1 ($F(1, 37)=23.49$; $p<.000$; $\eta^2p=0.39$), which is a poor rating. However, the difference between the two models is much smaller here than for loudness and annoyance (see Figure 7).
Overall, however, model 1, the model without “silence technology”, is perceived as statistically significantly louder, more annoying and more powerful (better performance) than model 2 (with “silence technology”). Therefore, the results are in line with hypothesis 1.

3.2.4 Correlations

All correlations were calculated by means of repeated measurements correlation with the software R [19]. There is a strong positive correlation between perceived loudness and annoyance ($r_{rm}(679)=0.69$; $p<.000$), a moderately strong correlation between perceived loudness and perceived performance ($r_{rm}(679)=0.46$; $p<.000$), and a weak correlation between perceived performance and annoyance ($r_{rm}(679)=0.24$; $p<.000$). Thus, the results are in line with hypothesis 2 – 4.

4 Discussion

In the present study, two vacuum cleaner models, one with and one without a “silence technology” were evaluated in an UX as well as in a listening test (psychoacoustic evaluation). In the UX test, the UEQ+ was used to evaluate the properties of efficiency, acoustics, haptics, usefulness and intuitive use. In addition, the perceived importance of the respective properties was surveyed. In the listening test, 18 vacuum cleaner sounds (from different vacuum cleaner models vacuuming on 3 different floorings and in 3 different operation states) were evaluated in terms of their perceived loudness, annoyance, and power level using semantic differentials.

The results show that the model with “silence technology” (model 2) was perceived as quieter, less annoying but also as less powerful. In addition, a strong positive correlation between loudness and annoyance as well as a medium positive correlation between loudness and power level was shown.
The UX test shows a similar result. The model with “silence technology” (model 2) performed better than model 1 regarding overall UX and the acoustic scale of the UEQ+. The different aspects of UEQ+ used in this test are also differing in importance. Haptics is perceived as the least important. This is followed equally by acoustics and usefulness and then, at a considerable distance, by intuitive use, as well as efficiency. Maslow's Pyramid of needs could provide an explanation for this results [20]. On the first level of Maslow’s Pyramid are the basic needs. For a vacuum cleaner, the basic need is that it reliably cleans surfaces. This basic need is described in the UEQ+ by “efficiency” which is perceived as most important by the participants. On the next level of Maslow’s Pyramid there’s the level of safety. For a vacuum cleaners, this includes being able to operate it reliably and explains why intuitive use is the second most important. Both acoustics and haptics are features that tend to satisfy individual needs. Thus, they would be on the level of self-actualization und would be satisfied at last. This could explain why acoustics is considered rather unimportant, but is statistically significantly more important in model 2 than in model 1. In model 2, the basic properties such as efficiency and intuitive use are fulfilled much better than in model 1. As a consequence, the properties that serve self-actualization could also be perceived as more important. Nevertheless, there is a high potential for improvement in the area of acoustics for the overall UX in both vacuum cleaner models, as the results of the UEQ+ showed.

5 Conclusions

Overall, this study replicated the results of other studies evaluating the acoustics of vacuum cleaners. In addition, insights were gained into the UX of vacuum cleaners and how it can be improved, although the study results currently do not allow any direct conclusions about how strongly the acoustics influence the overall UX. Further studies are planned to answer this question.
In future, especially the human-centered acoustic optimization should be considered. For this purpose, the data collected in listening tests (perceived annoyance, loudness and efficiency) can be analysed with respect to objective psychoacoustic parameters and prediction models for the perceived annoyance or perceived performance of vacuum cleaners can be developed. In this way, the overall acoustic impression of vacuum cleaners can be improved in the design process to enhance the user experience. Furthermore, the optimal trade-off between annoyance and perceived performance could be defined and met in sound design processes. As the preliminary study showed, this could increase sales as consumers are willing to pay 14% more for better acoustics [1]. Furthermore, a trade-off between optimal performance and annoyance could be determined in further studies.
Finally, the acoustics of cordless vacuum cleaners should be given particular attention in future, as these are increasingly conquering the market. Here, improving the acoustics is much more challenging because of weight and space issues but could essentially contribute to a better user experience and thus lead to a competitive advantage of the manufacturer.

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