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Perception of sound quality of product sounds
A subjective study using a semantic differential

David Hülsmeier[1,2]; Lena Schell-Majoor[1]; Jan Rennies[1]; Steven van de Par[2,1]

[1] Fraunhofer IDMT, Hearing Speech and Audio Technology, Oldenburg, Germany

[2] Carl von Ossietzky Universität Oldenburg, Acoustics group, Oldenburg, Germany

ABSTRACT

How can quality of product sounds be measured? This question was investigated on basis of shaver, vacuum cleaner and spray sounds, which were matched in loudness according to DIN45631 and were separately presented to subjects. Using open questions, the perception of the sounds was determined and a list with word pairs was created as a basis for a semantic differential. The sounds were presented to subjects in a listening booth and were rated separately for each product group.

The data were analysed by means of polarity profiles and factor analyses. Groupings could be found for sounds and word pairs. For the word pairs, one factor representing quality could be found for each product group. This factor, the factor loadings and the answers of the subjects were used as basis for a linear model. The results indicate that spectral and temporal properties of spray sounds correlate with perception of quality. Stationary spray sounds were rated with a high quality in contrast to spluttering sounds. Vacuum cleaners need to sound powerful and functional to be perceived as top quality. Precise, cutting and fast sounds were perceived as top quality for shavers. The results are discussed on basis of auditory models.

Keywords: Sound Quality, Household Products

I-INCE Classification of Subjects Number(s): 04.3 12.4.4, 12.4.5

1. INTRODUCTION

Sound quality of product sounds has become a major factor in today's industry, especially in the field of automotive research eg. (1). Comparable studies for household appliances, like electric shavers, vacuum cleaners and spray cans are rare and thus are an interesting field of research. Finding suitable methods to compute product sound quality leads to a great advance in the assessment process. Time consuming studies with test subjects could be omitted due to objective models. To determine the sound quality of given household appliances and create an objective model, two questions arise:

- Which methods are suitable for a subjective determination of sound quality?
- What is a proper basis for an objective model?

These questions were investigated using a semantic differential and the sounds of shavers, vacuum cleaners and spray cans in idle mode.

Suitable word pairs, required for the semantic differential, were obtained by iterative questioning subjects during a preliminary study. Words pairs, describing sound quality, were added and used as an anchor.

Subsequently a main study was performed. The subjects were asked to rate the different sounds using the word pairs. All sounds were rated twice. Between the measurements an interview was performed to assess the subjective perception of the sound quality.

The results of the semantic differential were analysed with a principle component analysis to find common denominators. The necessary word pairs to describe the different product groups were reduced using Cronbach's α while maintaining the describing components. The Kaiser-Meyer-Olking-Criterion was applied to determine the adequacy of the data for a factor analysis.

Concluding this study, the subjective results were compared to weighted combinations of modelled sharpness, tonality and roughness. These comparisons were exploited to create models determining sound quality for each product group.

[1] [david.huelsmeier;lena.schell.majoor;jan.rennies;steven.van.de.par]@idmt.Fraunhofer.de

[2] [david.huelsmeier;steven.van.de.par]@uni-oldenburg.de

2. STATE OF THE ART

In (2) sound quality of hand-held power tools was investigated. An overall grade G and the desire to buy a device was measured using a semantic differential. These two measures show a high correlation. The concept of product-sound quality is described as "the adequacy of the sound attached to a product (3)". Especially if all apparent and desired features of the product are audible to the user, a high sound quality is perceived. Thus the overall grade G and the desire to buy a device are connected to the perceived sound quality. The relation of tonality towards sound quality was tested but regarded as insignificant.
A study investigating vacuum cleaners was conducted by E. Altinsoy et al. (4). Annoyance metrics were used to describe sound quality. It was found that the perceived annoyance was influenced most by loudness, sharpness and the tone-to-noise ratio.
H. Yanagisawa et al. described in (5) and (6) the kansei quality in product design. It was stated to be a product quality evoking "customer's specific impressions, feelings, and emotions". Furthermore he described "a method for extraction diverse and latent evaluation criteria of kansei quality". This method included two sensory tests. The first was conducted using sounds of existing products and the second is conducted with existing and composite sounds. The composite sounds were altered to have an increased kansei quality. A semantic differential was used to describe the existing product sounds. Applying the results of the semantic differential, the composite sounds were created. Another semantic differential was conducted using existing and composite sounds. Given the results of both sensory tests H. Yanagisawa et al. extracted potential factors of kansei evaluation criteria. They used loudness, sharpness, roughness and fluctuation strength as measurable design parameters for product sound quality. Those metrics were used to formalise the factors found with a principal component analysis. Like in (4), it was shown that loudness, sharpness and the tone-to-noise ratio were important metrics related to product sound quality.
Various other approaches were conducted to make product sound quality and tangible. To mention two further examples H. Fastl investigated a method to neutralise the meaning of sound (7) and Takada et al. focused on the impact of temporal structures on sound quality of copy machines (8).

3. METHODS

In this study the following measures and methods were applied. An extensive description can be found in (9).

3.1 Cronbach's Alpha

Cronbach's α is a statistical measure to determine the internal consistence of a scale. The mean correlation $\bar{r}$ between descriptors is utilised:

$$\alpha_{norm} = \frac{N \cdot \bar{r}}{1 + (N-1) \cdot \bar{r}} \quad (1)$$

N is the number of descriptors, and α_{norm} the normalised Cronbach's Alpha. α_{norm} ranges from $-\infty$ to 1. If α_{norm} is larger than .9, the internal consistence is excellent. Values ranging from .8 to $<$ .9 are described as good. Its use is to determine redundant word pairs.

3.2 Kaiser-Meyer-Olkin-Criteria

The Kaiser-Meyer-Olkin-Criteria (KMO) is a measure of sampling adequacy. It is used to determine if the data are suited for a factor analysis. Values between .7 to $<$ .8 are described as middling and from .8 to $<$ .9 as meritorious (10).

3.3 Semantic Differential

The semantic differential is a method to scale characteristics of sounds with verbal descriptors and n-point scales (11) (Fig. 1). The verbal descriptors are used as extreme values. The further the rating of a subject approaches one word, the higher the agreement.

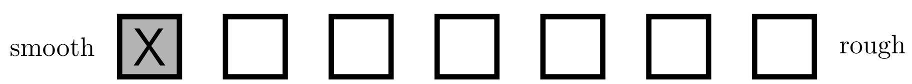


Figure 1 – Exemplary 7-point scale used in semantic differentials to rate sounds with verbal descriptors as indicated.

3.4 Principle Component Analysis

The principle component analysis (PCA) is used to find superior structures in a data set. For this purpose n subjects rate p features. This procedure builds a $n \times p$ matrix F which can be displayed in a q dimensional space. The number q of dimensions to consider is accessed by counting the singular values $\lambda \geq 1$ of F (Kaiser-Criteria). Alternatively the screeplot criteria can be applied: All singular values are sorted from largest to smallest and plotted. In such a plot a break of slope becomes visible. The number of singular values before the break of slope is equal to q. Subsequently the axis are rotated using orthogonal or oblique rotation methods. In this work the Kaiser-Criteria was applied and an orthogonal varimax rotation was used.

4. STIMULI

The sounds of three product groups, nine electric shavers, nine vacuum cleaners and seven spray cans in idle mode, were recorded. The recordings were made inside of an anechoic room. Furthermore the loudness of the sounds was modelled as described in (12). Afterwards their level was adjusted between 60 and 70 dB SPL such that their loudness differed by no more than $\pm .5$ sone. This was done due to the assumption that loud sounds are automatically perceived as annoying and quiet sounds as more pleasant. Thus other psychoacoustic quantities, as sharpness, were not influenced by differing loudnesses and could be investigated in-depth.

5. LISTENING TESTS

For assessing the sound quality of the recorded sounds, two listening tests were executed. At first a preliminary study was carried out to find suitable word pairs for rating the product groups. Subsequently a main test was carried out, in which subjects were asked to rate the sounds.

5.1 Preliminary test

Ten subjects were asked to describe the sounds during sound exposure. The aim was to create a list of various discriminative words. This list was expanded by the supervisor with words describing sharpness, tonality, roughness and quality if required. Subsequently five subjects were asked to identify antonyms of the previously found words and to form word pairs. During the last step, the suitability of the word pairs to the stimuli was rated. The 24 best word pairs were used for further investigation (fig. 2). This process was carried out separately for each product group.

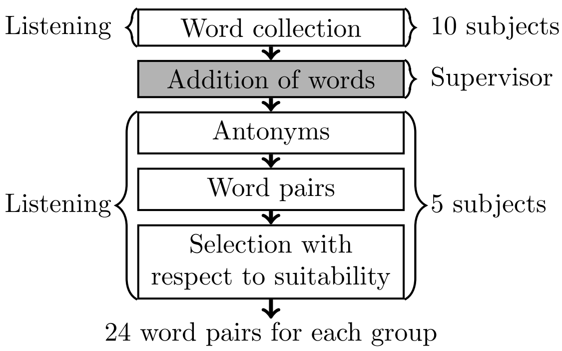


Figure 2 – Outline of the preliminary test. It was conducted to find suitable word pairs for further investigation.

5.2 Main test

The subjects rated the different stimuli using a semantic differential and the word pairs resulting from the preliminary test. For this purpose three appointments were scheduled with each subject. All appointments proceeded identically (fig. 3) with the exception that the order of sound groups was randomised for each subject. At first a written instruction was handed to the subjects describing their task. Next the subjects were seated in a listening booth to rate the stimuli of a product group. Before the rating procedure started, all stimuli and word pairs used in the semantic differential were presented. Consecutively a seven point scale was taken to rate the sounds (e.g. fig. 1). Afterwards a standardised interview was performed with the subjects. They were asked if they use the product, as well as if characteristics of the sounds attracted their attention. Furthermore, they were asked to point out traits of high-quality and low-quality product sounds. The last task of the appointment was to rate the sounds of another product group. Each measurement took about 20 minutes and was carried out twice for each product group.
In total seven female and nine male subjects participated in the main test. Nine of them were considered to be expert listeners due to their previous experience with listening experiments. All stated to have a normal hearing. Their average age was 25.6 years.

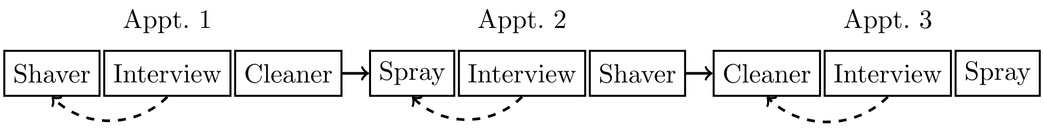


Figure 3 – Exemplary outline of the experiment schedule. Three appointments were arranged, each included the rating of a product group, e.g. shavers, an interview about the previous experiment and finally the rating of a different product group.

6. RESULTS

The data obtained from the measurements were analysed using a principle component analysis. The amount of factors to consider was determined by the Kaiser-Criteria. This was done for each product group separately. Afterwards redundant word pairs were excluded using Cronbach's Alpha while keeping all found factors and increasing the internal consistency of the scales. To identify the factor describing quality, an anchor word pair was used (high quality - low quality). During the listening test German word pairs were used. They were translated from German to English by a native American.

6.1 Shavers

For shavers four different factors were found (tab. 1). The word pairs with a high loading on the quality factor were cutting - ripping, precise - imprecise, sharp - blunt and rough - smooth. The other 3 factors can be described as metallic (tinny - dark), pleasantness (pleasant -uncomfortable) and spectral extent (humming). They explained 77.43 % of the variance s_{rot}^2 of the data. The KMO was equal to .798, which denotes a middling adequacy. Cronbach's Alpha was .862. This denoted a good internal consistence of the used word pairs.
Subjects described fast shavers with a constant sound, keeping the pitch as top quality. On the contrary fluctuations as well as tonal and shrill sounds were perceived as low-quality.

6.2 Vacuum cleaners

The performance and condition of vacuum cleaners, thus their quality, was described by the word pairs powerful - weak, efficient - inefficient and functioning - broken (Tab. 2). Three further factors were found, namely pleasantness (pleasant - annoying), spectral extent (howling) and temporal structure (smooth - rough). 79.38% of s_{rot}^2 were explained with these factors. The KMO for vacuum cleaners was .873, denoting a meritorious adequacy. With $\alpha_{norm} = .949$ an excellent internal consistence was reached.
The words calm, monotone, constant and low were used by subjects to describe high-quality sounds. Whistling and peeping were used to describe low-quality sounds.

6.3 Sprays

The quality of spray sounds was connected to the perceived temporal structure. This was indicated by consistent - spluttering, calm - shaking and swooshing - rattling, as well as smooth - rough. Additional two other factors were found describing the spectral extent (dull - piercing) and the metallic perception (metallic - artificial). In total 73.13% of the variance s_{rot}^2 was explained with these factors. A meritorious KMO of .842 and an excellent α_{norm} of .910 was reached for spray sounds.
The answers given in the interview yield that constant sounds were perceived as high-quality for spray cans. The word spluttering was used to describe low-quality sounds.

7. MODEL

Using the results of the PCA, factor scores $\overline{F}_{j,a,norm}$ were calculated (9). This was done for the factor j identified as quality and for each sound a (eq. 2). b_{nj} denotes the factor loading and $X_{n,p,a}$ the rating of the subjects p. The index n represents the word pairs. $max(Rating)$ denotes the maximal possible rating and was used to normalise $\overline{F}_{j,a,norm}$. The results are displayed in table 4.
Next the psychoacoustic quantities sharpness S [in Acum], tonality T and roughness R [in Asper] were modelled for each sound using the SIP-Toolbox (13). It includes models for S (14), T (15) and R (16). Sharpness, tonality and roughness were concatenated using weights to obtain the objective quality Q_{obj} (eq. 3). The best fitting weights were found using the minimum mean squared error (MMSE) of the data set.
The highest Pearson correlation for shavers was $r_{shaver} = 0.44$ (eq. 4). For vacuum cleaners a higher correlation of $r_{cleaner} = 0.87$ was found (eq. 5) and for spray cans a correlation of $r_{spray} = 0.75$ was determined (eq. 6, see fig. 4). A high score on Q_{obj} and $\overline{F}_{j,a,norm}$ implies a low sound quality of the appliance and vice versa.

Table 1 – Results of the semantic differential for shavers. The word pairs were translated, by a native American, for this paper.

Word pairs				1	2	3	4	
high	deep	hoch	tief	-.880	.127	-.170	.094	metallic
tinny	dark	blechern	dunkel	-.822	-.094	.019	-.223	
tall	small	groß	klein	.821	-.081	-.051	.104	
muffled	shrill	dumpf	schrill	.811	-.230	.318	-.172	
cutting	ripping	schneidend	reißend	-.030	.866	-.174	-.030	quality
precise	imprecise	präzise	ungenau	-.130	.842	-.088	.303	
high quality	low quality	hochwertig	minderwertig	.313	.742	.244	.304	
sharp	blunt	scharf	stumpf	-.481	.687	-.207	.201	
rough	smooth	rau	glatt	.319	-.616	-.293	-.083	
meddlesome	cautious	aufdringlich	zurückhaltend	-.147	.075	-.918	.056	pleasantness
silent	loud	leise	laut	-.086	-.178	.893	-.166	
pleasant	uncomfortable	angenehm	unangenehm	.315	.339	.779	-.032	
humming	not humming	summend	nicht summend	.000	.114	-.019	.901	spectral extent
tonal	not tonal	tonhaltig	nicht tonhaltig	.069	.244	-.193	.695	
			s^2_{rot} / %	24.0	22.6	18.9	11.8	∑77.43%

Table 2 – Results of the semantic differential for vacuum cleaners. The word pairs were translated, by a native American, for this paper.

Word pairs				1	2	3	4	
powerful	weak	kraftvoll	schwach	.895	.098	.089	.082	quality
efficient	inefficient	effizient	ineffizient	.893	.198	.090	.166	
functioning	broken	funktionstüch	kaputt	.805	.306	.139	.238	
high quality	low quality	hochwertig	minderwertig	.802	.430	.162	.177	
loud	silent	leise	laut	.046	.877	.204	.152	pleasantness
soft	hard	weich	hart	.358	.796	.197	.002	
pleasant	annoying	angenehm	störend	.384	.788	.290	.160	
sharp	dull	scharf	gedämpft	-.355	-.723	-.392	.049	
tonal	not tonal	tonhaltig	nicht tonhaltig	-.015	-.113	-.821	.028	spectral extent
howling	not howling	heulend	nicht heulend	-.052	-.285	-.727	-.327	
swooshing	whistling	rauschend	pfeifend	.260	.432	.695	.032	
buzzing	singing	brummend	singend	.341	.398	.640	-.171	
monotone	irregular	monoton	unregelmäßig	.221	.008	.229	.845	temporal structure
steady	alternating	gleichförmig	schwankend	.315	-.029	.116	.831	
smooth	rough	glatt	rau	-.032	.224	-.297	.755	
			s^2_{rot} / %	24.2	22.4	17.5	15.2	∑79.38%

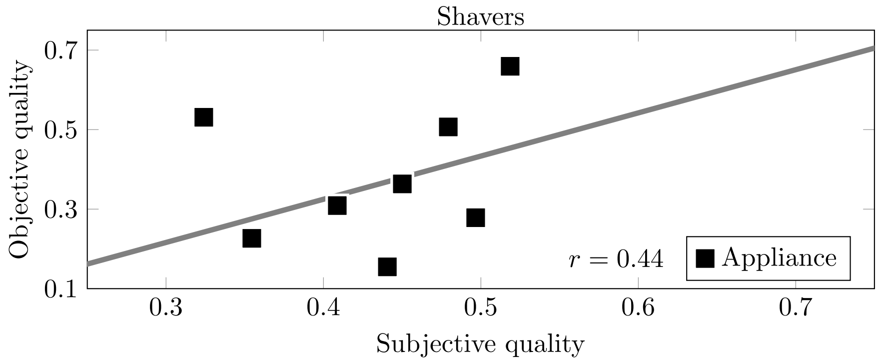
$$\overline{F}_{j,a,norm} = \frac{\sum_p^P \sum_n^N b_{nj} \cdot X_{npa}}{P \cdot N \cdot max(Rating)} \quad (2)$$

$$Q_{obj} = x_1 S + x_2 T + x_3 R \quad (3)$$

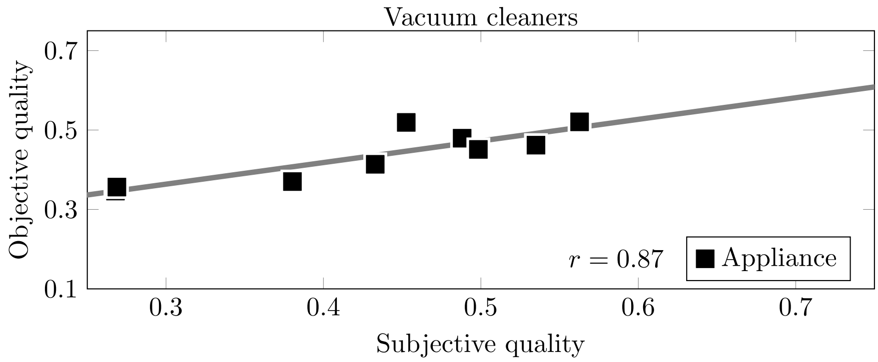
$$Q_{obj,Shaver} = 0.59 \cdot T - \frac{0.26}{Asper} \cdot R \quad (4)$$

$$Q_{obj,Cleaner} = \frac{0.24}{Acum} \cdot S + 0.23 \cdot T \quad (5)$$

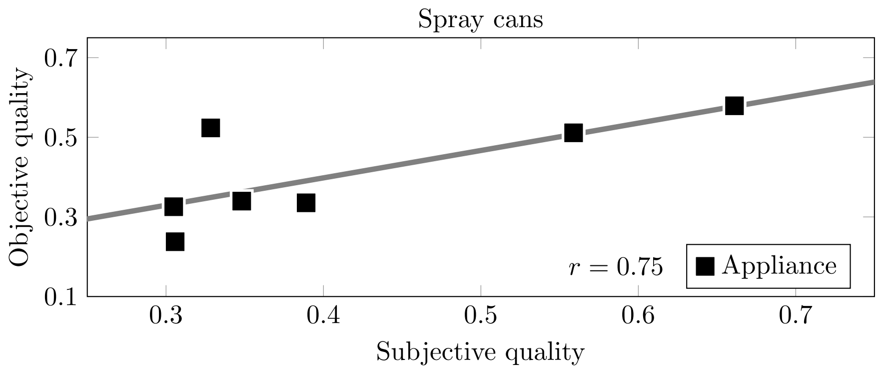
$$Q_{obj,Spray} = 0.61 \cdot T + \frac{3.43}{Asper} \cdot R \quad (6)$$



(a) Objective versus subjective sound quality of shavers. Objective sound quality was modelled using a linear combination of sharpness and tonality. In this case a Pearson correlation coefficient of 0.44 was calculated.



(b) Objective versus subjective sound quality of vacuum cleaners. Objective sound quality was modelled using a linear combination of sharpness and tonality. A high correlation of objective and subjective quality was reached ($r = .87$).



(c) Objective versus subjective sound quality of sprays. Objective sound quality was modelled using a linear combination of roughness and tonality. A good correlation of $r = .75$ was determined.

Figure 4 – Comparison of the subjective quality F and the objective Quality Q_{obj} for the different product groups.

8. DISCUSSION

8.1 Listening tests

A preliminary test for a semantic differential is mandatory, finding suitable word pairs is quite important. Like the base of a house, the quality of the results is depending on it. The here realised preliminary test was sufficient to find word pairs describing sound quality of cleaners, shavers and spray cans. A more elaborate but time-consuming approach was proposed in (17). 17 subjects were asked to describe automotive sounds during a free verbalisation interview. This took place while listening to the sounds. In total 682 descriptive terms were found, which were reduced to 24 to 36 word pairs for different states of vehicles. Thus the most suitable word pairs could be found. If possible, this procedure should be used to determine the word pairs.
Presenting the sounds and word pairs prior to the rating procedure clarifies the task of the subjects and final questions can be asked.

8.2 Results

Shavers have a high sound quality if they are cutting, precise, sharp and smooth. These terms also describe the desired features of electric shavers as stated by the subjects. The last two word-pairs (tab. 1), namely sharp - blunt and rough - smooth, showed to be ambiguous. Expert listeners stated to connect them to the psychoacoustic measures sharpness and roughness as well as the mechanical sharpness of the razor blade and the result of the shave. Thus the meaning of them has to be clarified before the experiment.
The word pairs describing the sound quality of vacuum cleaners are related to power, efficiency and proper working order. Those characteristics are relevant to and desired by the users.
Temporal properties of spray sounds relate to the perceived quality. If a spray is spluttering, shaking, as well as rattling, a low sound-quality is achieved. This is due to the temporal structure of the spray jet. One subject stated that a steady sound denotes an evenly spread substance, which is again a desired feature of sprays. Spluttering sounds yield the impression that a spray can is nearly empty, which is not desired. cognitive,

8.3 Model

The linear models can describe the quality of vacuum cleaners and spray cans properly. This is shown by $r_{clenaer} = 0.87$ and $r_{spray} = 0.75$. Even though the descriptive words for sharpness and tonality are not included in the quality factor of vacuum cleaners, they can be used to model the objective quality. At least a mediocre loading of the word pairs sharp - blunt and tonal - untonal on the quality factor could be expected (tab. 2) but is not reached. Hence further experiments should be conducted to confirm this relation.
For spray cans the connection to roughness is given by the word pair smooth - rough. The objective model (eq. 6) as well as the factor loading (tab. 3) shows a high impact of roughness on the perceived sound quality.
In the case of shavers a mediocre correlation was reached. Thus the proposed model is inaccurate and further data need to be gathered and analysed. Also the the ambiguity of rough - smooth is supported. In eq. 4 increasing roughness states to increase the objective quality. Taking the factor loading of the word pair rough - smooth into account (tab. 1, $b = -.616$), quality increases, if the sound is perceived as smooth. This is a contradiction to the model.

8.4 Future research

To create sophisticated models for the different product groups, the detected word pairs can be used. Hence further sounds can be studied to fortify the results and models. Also the impact of loudness could be considered and researched. The results (tab. 1 and 2) indicate that loudness (loud - silent) has a minor influence on quality. This can be caused by the narrow loudness range of the sounds. Concluding these ideas, two questions arise:

1. What is the optimal loudness (*sharpness/tonality/roughness*) to maximise the perceived sound quality?
2. Do the models hold for further sounds?

9. SUMMARY

In this work a procedure was proposed to find suitable word pairs to use in a semantic differential for arbitrary sounds. Quality relevant word pairs were determined for electrical shavers, vacuum cleaners and spray cans. Using the results of the experiment, factor scores for quality were calculated for each individual appliance. These factor scores were compared to objective measures, namely sharpness, tonality and roughness. Proper models were found for vacuum cleaners and spray cans. A mediocre model was proposed for shavers.

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Table 3 – Results of the semantic differential for spray cans. The word pairs were translated, by a native American, for this paper.

Word pairs				1	2	3	
consistent	spluttering	gleichmäßig	stotternd	.907	.056	-.013	structure and quality
calm	shaking	ruhig	zitternd	.898	.156	.009	
high quality	low quality	hochwertig	minderwertig	.868	.148	.030	
swooshing	rattling	rauschend	rasselnd	.844	.009	-.150	
smooth	rough	glatt	rau	.844	-.070	.007	
pleasant	uncomfortable	angenehm	unangenehm	.667	.473	.262	
dull	piercing	dumpf	stechend	.075	.891	-.004	spectral extent
blunt	sharp	stumpf	scharf	-.072	.857	-.145	
deep	high	tief	hoch	.139	.815	-.089	
metallic	artificial	metallisch	künstlich	-.178	-.117	.763	metallic
blowing	sucking	pustend	saugend	.298	-.011	.685	
tinny	dark	blechern	dunkel	-.419	-.509	.530	
			s^2_{rot} / %	38.2	22.9	12.1	$\sum$73.13%

Table 4 – Quality ranking R with corresponding factor score $\overline{F}_{norm}$. The lower the score, the better the appliances.

Vacuum cleaner		Shaver		Spray cans	
R	$\overline{F}_{norm}$	R	$\overline{F}_{norm}$	R	$\overline{F}_{norm}$
Cleaner 1	.2679	Shaver 8	.3097	Spray 5	.3049
Cleaner 2	.2688	Shaver 7	.3240	Spray 2	.3058
Cleaner 3	.3803	Shaver 1	.3545	Spray 7	.3284
Cleaner 6	.4329	Shaver 2	.4088	Spray 3	.3481
Cleaner 5	.4526	Shaver 3	.4406	Spray 4	.3890
Cleaner 8	.4881	Shaver 5	.4501	Spray 6	.5589
Cleaner 7	.4984	Shaver 4	.4793	Spray 1	.6611
Cleaner 4	.5350	Shaver 6	.4967		
Cleaner 9	.5627	Shaver 9	.5186		