Product Sound Quality – from Perception to Design

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This article on product sound quality is concerned with the relationships between the work of product designers and the perceptions of consumers regarding the acceptability of product sounds. Designers make choices regarding structure, materials and components in a product. The tools they use should allow them to anticipate the effect of these choices on sound quality. This discussion recounts the role of psychoacoustics in product design and product acceptability and notes the results of that work in metrics for sound quality and consumer/user perceptions about the product. The successes and drawbacks of this activity are noted. Recent work on a new paradigm using "Acoustical Sensory Profiles" as an intermediary between metrics and perception is described, along with some results using the procedure. Future developments are indicated.

I have spent more than 30 years working with products that are 'noisy.' But I learned very quickly that 'noisy' might not equate with 'loud.' A shop-type vacuum cleaner had a noise problem: a slight rattling in the motor during coast down after the unit was turned off, after the roar of the unit had died away! The roar was expected, but the rattling could indicate to the owner that there was a problem with the motor. The product could not be shipped until the rattle was eliminated.

Product sounds can be objectionable, but they can also be favorable. The sound of an automobile door closing is a classic example that has been studied for many years. Compare the sounds of doors closing on 2 cars, one of which costs 3 times as much as the other (Sounds A,B).[1] You can tell which one is the more expensive car. The first is an Audi A4; the second is a Ford Escort.

One GM engineer used the request of his product planners to further his education. When planners asked Don Malen to "Improve solidness of door closing sound without adding too much cost," he made it the topic of his Ph.D. thesis at the University of Michigan. Now, engineers might regard the charge as the typically vague request from a product manager, but it has the strength of saying what the product planners really wanted. Dealing with this charge required Malen to address issues in acoustical signal analysis, human perception, mechanism design and cost benefit analysis.

As long as products do not change very much, certain expectations grow with regard to their sounds. We come to expect products to have a certain type of sound. If a motor or gear sound in that product becomes too loud, we might be concerned or bothered by it, but a certain amount of sound from the motor or gearing is expected and acceptable. The vacuum cleaner rattle was unacceptable simply because it should not occur in that product.

But what about a product that is new? When the instant camera was introduced, it made a sound that was completely different from that of a 35 mm SLR camera (Sounds C,D).[1] If the product is different, then experience shows that the new sound can become acceptable, particularly if there is a difference in function, as there is with an instant camera.

Truly new products such as front loading washing machines (recently reintroduced into the U.S. market) or hybrid electric/IC engine automobiles may sound different from the products they hope to replace. Should the product manager simply try to make them as quiet as possible and hope for the best, or should the sound of these products be exploited as a product differentiation? Are there ways to help the product manager make that decision?

Since I believe a key element in dealing with these issues at present is through listening tests, let's look at the background of psychoacoustics. Psychoacoustics is the study of how people perceive sounds. A major tool of psychoacoustics is jury testing in which people are asked to listen to and judge sounds for certain characteristics.

Loudness and Annoyance

A great achievement of psychoacoustics has been the development of a scale of loudness, which is the perception of the strength of a sound. The loudness of tones was studied in the US by Fletcher and Munson[2] and in the UK by Churcher and King.[3] This work was then extended to the loudness of bands of noise and much more complex sounds. As a result there are computational algorithms or metrics for loudness that work extremely well for calculating and predicting how people will perceive the loudness of all kinds of sounds.

Until the 1950s, it was assumed that loudness would predict when product sounds were objectionable. But a new product, the jet air transport, shattered that idea. Jet airplanes that were equally loud as piston engine aircraft were much more annoying. Compare the sound of a piston engine aircraft (Sound E)[1] and a jet airplane (Sound F).[1] From the late 50s into the 60s a number of studies using listening tests were used to create a new algorithm (or metric) to predict the perceived noisiness of aircraft in PNdB (perceived noise decibels). This idea has been further developed into predicting degrees of annoyance around airports, in the U.S. called a Noise Exposure Forecast (see Figure 1).

It was quite a shock, therefore, when this new metric of noisiness or annoyance seemed only to predict the annoyance of jet aircraft and not, for example, roadside traffic noise (Sounds F,G).[1] It also failed to predict public acceptance of the sonic boom from supersonic aircraft, a sound that seemed to be unacceptable (like the rattling motor) if it was heard at all. A senior administration official opined that supersonic flight over voting populations would never be allowed.

The Dimensions of Product Sound

The metric for Perceived Noisiness turned out to be far less robust than the metric for Loudness. It was an early indication that the acceptability of a sound was product specific to a certain degree. Even the most cursory consideration of the sound of a product leads us to see that it has certain dimensions:

Strength or Magnitude – represented by metrics such as Loudness (Sones, Phons), A-Weighted Sound Level (dBA) and Speech Interference Level (SIL).

Annoyance Value – noisiness, roughness, sharpness (bothersome aspects of the sound, Perceived Noisiness, PNdB).

Amenity Value – regularity, harmonicity, appropriateness (the pleasing aspects of the sound, no metric).

Information Content – identification, performance and condition of the product, appropriateness (no metric).

All of these factors combine to determine how acceptable the sound of a product will be to users. That total response of acceptability is my definition of Sound Quality. In other words, Sound Quality is a perceptual reaction to the sound of a *prod-*

This article is based on a presentation of the same title at the joint meeting of Noise-Con 2000 and the 140th meeting of the Acoustical Society of America in December 2000 at Newport Beach, CA.

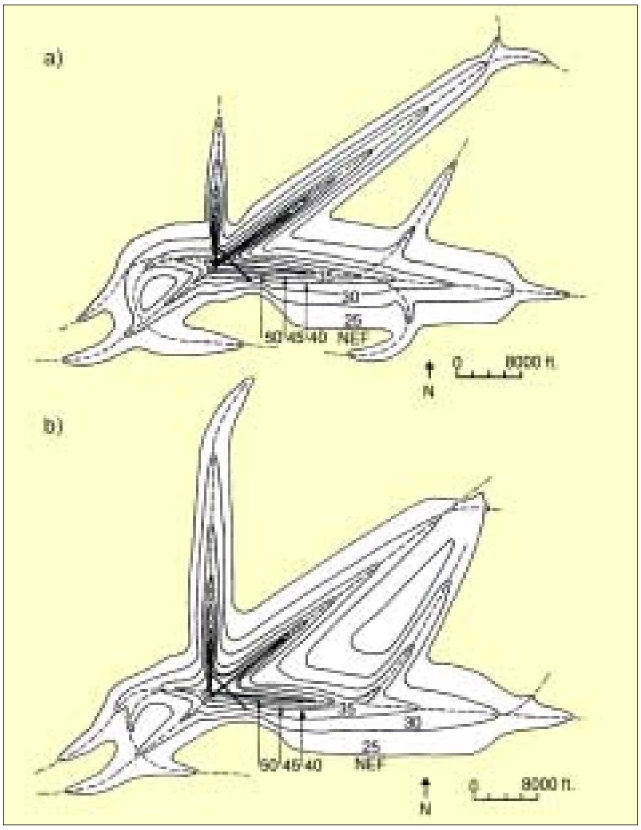

Figure 1. Noise Exposure Forecast (NEF) contours for the operations of El Paso International Airport, El Paso, TX: (a) 1970, (b) 1976.

Figure 2. Harley-Davidson advertisement.

uct that reflects the listener's reaction of how *acceptable* the sound of that product is; the more acceptable, the better the SQ rating. Sound Quality is the response of people, not a meter. It is specific to the product. "A good lawn mower does not sound like a good refrigerator." The key word here is 'acceptable,' which depends on the situation of use, expectation and other factors.

One of those other factors is one's attitude toward the noise maker. The sound of my friendly neighbor mowing his lawn and making the neighborhood nicer is acceptable, but the equally loud sound of the motorcyclist invading my quiet suburban street is not. A study of reaction to freeway noise in Los Angeles found an inverse relation between noise level and annoyance. Those close to the freeway expected the sound and were benefited by lower home prices. The sound was louder, but less bothersome. Those further away felt the noise to be an inappropriate intrusion into their nicer neighborhoods. Their sound was weaker, but they were more troubled by it.

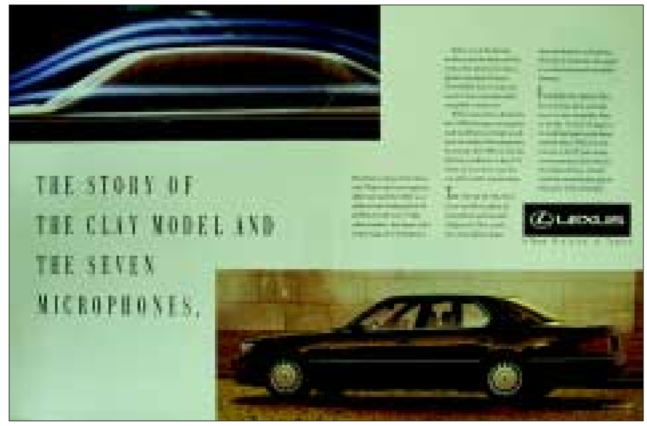

Figure 3. Lexus advertisement.

Figure 4. Whirlpool advertisement.

The character of a sound can be favorable or unfavorable, depending on our expectation and experience. For example, it is widely accepted that modulation in mechanical sounds is undesirable. The sound of gearing in a golf car caused the manufacturer to reject drive components (Sound H).[1] But modulation in music is very desirable (Sound I).[1] And, interestingly, both reactions have the same cause – modulation captures our attention. We want to hear the musical note, but we do not want to hear the gearing mechanism.

Sound as a Marketing Opportunity

If product sound has both good and undesirable features, are there ways to favorably present a product with regard to its sound? There are many examples of companies doing just that. A Harley-Davidson catalog contained a recording of its sound (Figure 2, Sound J).[1] The company applied to have the sound trademarked, like the 3 chimes of the NBC network. Although their application has been dropped, they maintain and many agree that the sound identifies their product.

Lexus automobiles are known for the excellence of their interior quietness (Figure 3) and both their television and print advertising associate that quietness with sophistication (symphony orchestras) and advanced technology (wind tunnels).

In the area of products for the home, examples include television advertising by Hunter (overhead fans) that associates the quietness of their fans with the comfort and security of the home. Television and print advertising for Whirlpool dishwashers claim that their dishwashers do not interfere with

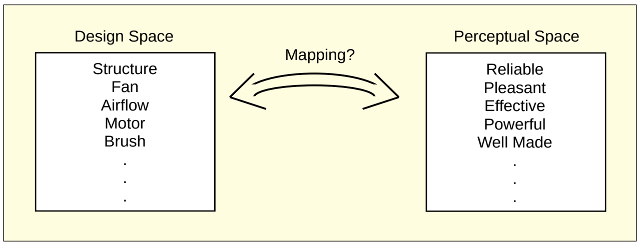

Figure 5. Vacuum cleaner example for the product SQ design problem.

conversations around the breakfast table or when using the telephone (Figure 4).

Manufacturers can learn whether or not product sound is an issue for their products in a variety of ways. Focus group sessions can be designed to determine the importance of sound as a feature (Table 1), and service representatives, dealers and customer letters and calls are all sources for information about the importance of sound to the customer. If the company decides that sound is an issue, then jury testing is carried out to determine what the goals for product sound should be, and how they can be achieved through choices of materials and components.

Acoustical Sensory Profiles and Jury Testing

Customers make judgements about product sound in terms of its loudness, annoyance, amenity and what it says about the product. In other words, customers make their judgements based on a product's Sound Quality. Product Planning tries to take information about those judgements and specify to designers what needs to be accomplished regarding the sound, as we saw for the door closure sound. The product team therefore has to make the transformation between the judgements of users and the engineering choices for structure, gearing, motors, fans, electrical components, etc., that make up the product. The process needs a mapping between the two (Figure 5).

There is no question that we can faithfully record the sound of the product, but we do not know the algorithm or metric to convert that signal to an "acceptability rating." The taste and flavor industries have a similar problem; they don't know what to measure. Those industries have used panels of trained experts to establish "Sensory Profiles" for their products (Figures 6-7). Products are rated according to descriptive words (a lexicon), and the product that best matches the favored profile is deemed the best.

Table 1. Washer sound focus group discussion guide.

I. Introduction
- A. Moderator introduction, taping, open discussion, etc.
- B. Respondent introduction . . .
  1. Household Size
  2. Working vs. non-working
  3. Number of loads of laundry processed weekly

II. Washer Background
- A. Washer brand, size, age
- B. Location of washer
- C. Briefly tell me about your washer
  – What do you like/dislike about your washer?
- D. Using a scale of 5 to 1, where 5 means very important and 1 means not important, please rate how the following affects your satisfaction with your washer.
  – Large capacity
  – Color
  – Sound
  – Cycle selection
  – Vibration
  – Ease of loading
  WRITE THIS NUMBER ON YOUR PAD
- E. Thinking about your washer, do you hear it operating?
- F. Tell me about the sound your washer makes.
  1. How would you describe the sounds?
  2. What, if anything, do the sounds your washer makes communicate to you?
  3. Describe how you like the sounds the washer makes.
  4. What are the most important sounds that you hear? Why?
  5. What words would you use to say how well the machine was working?

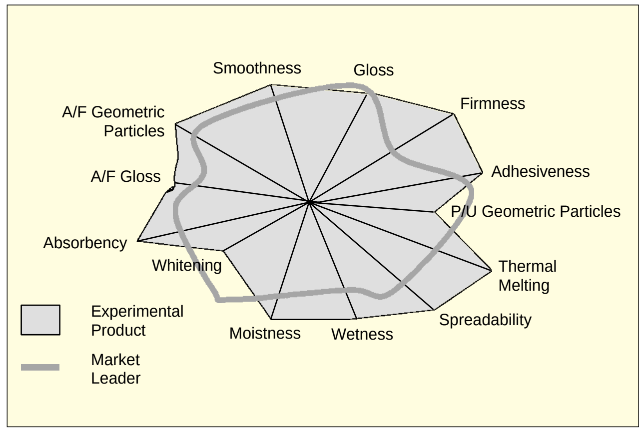

Figure 6. Sensory profiles of two skin care products.

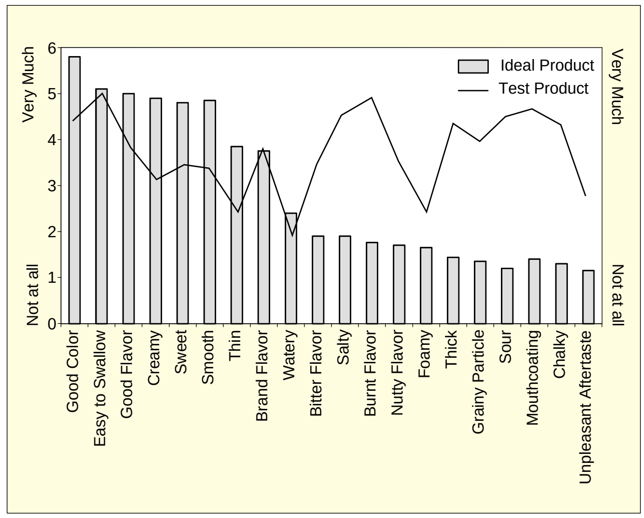

Figure 7. Bar graph of peanut butter sensory profiles.

My company has carried out research on SQ design sponsored by our National Science Foundation in its Program for System Dynamics and Controls. A goal of that effort has been to develop the mapping just discussed using Acoustical Sensory Profiles (ASPs). We believe that we have arrived at metrics that are helpful in predicting consumer responses, using as the intermediary an Acoustical Sensory Profile for a particular product type. Our initial research has involved developing ASPs for the sounds of vacuum cleaners and washing machines.

An early job was to develop a lexicon of descriptive words for product sounds. My personal review of 23,000 words of the English language revealed about 1300 that had to do with sound. Inspection of that list indicated 3 categories of words:

Table 2. 62 descriptors for sound grading.

bassy	dull	jangling	rhythmic	ticking
booming	echoey	knocking	ringing	tinny
bright	even	mellow	roaring	tonal
buzzy	grating	melodic	rumbling	uneven
clanking	grinding	modulated	sharp	vibratory
clear	groaning	pinging	shrill	whirring
damped	gurgling	pounding	smooth	whistling
deep	gushing	pulsing	soft	muffled
discordant	harsh	purring	soothing	open
distant	hissing	rapping	squeaking	piercing
distorted	hollow	raspy	strong	
dripping	humming	rattling	swooshing	
droning	impacting	resonant	thin	

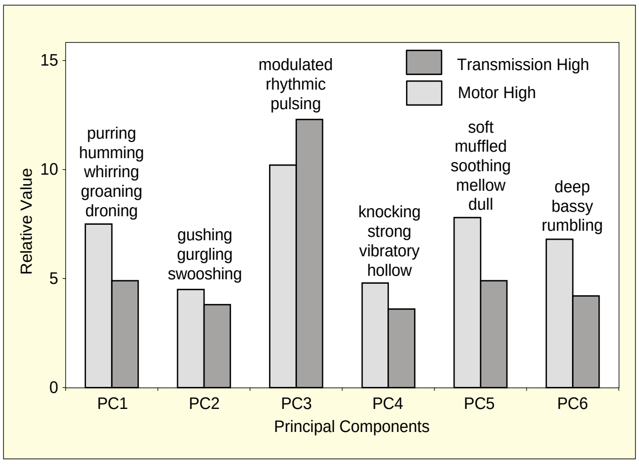

Figure 8. Principal component reduction of vacuum cleaner sensory profile.

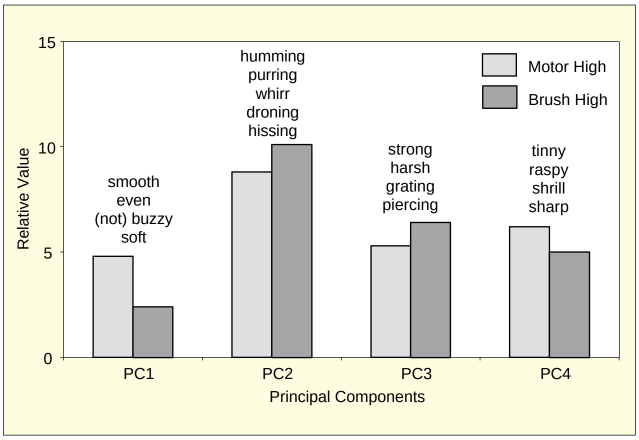

Figure 9. Principal component reduction of washing machine sensory profile.

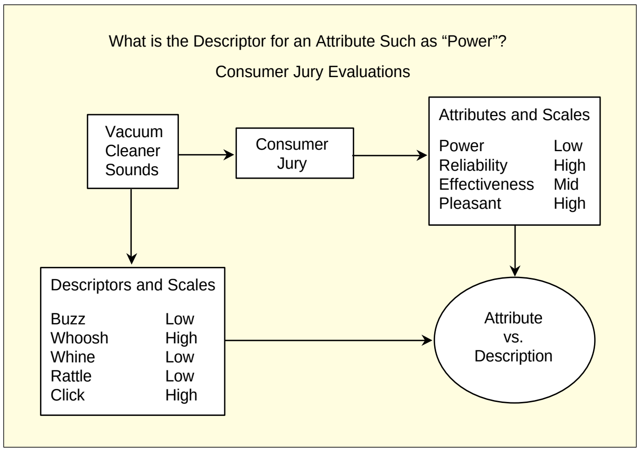

Figure 10. A jury listening panel can judge the product based on its sound and also use the "expert's vocabulary" to describe the sounds.

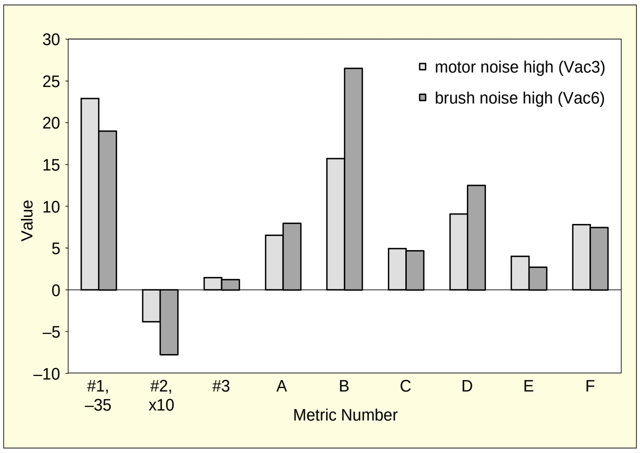

Figure 11. Comparison of physical metrics for two vacuum cleaner sounds.

those that described the maker of the sound (bell or bell-like), those that describe our response to the sound (alarming, cheering) and those that describe the sound itself (ringing). It was the descriptive words we were after, but there were more than 400 of those. By eliminating words that were very close (ringing and pealing) and others that were infrequently used, we got our lexicon down to 62 words (Table 2).

Our 15 member expert panel consisted of persons experienced at being articulate about sounds – musicians, recording engineers and psychoacousticians. This group was presented with sounds of washing machines (Sound K),[1] vacuum cleaners (Sound L)[1] and other natural sounds. They graded each sound along a scale for each of the 62 descriptors. Therefore the response of each expert listener to a sound is a point in a 62 dimensional space. This space is rotated and distorted to achieve the tightest possible clustering of responses from our expert panel. The coordinates along which the best clustering is achieved are the "principal components" (PCs) and become the dimensions of our Acoustical Sensory Profile (ASP).

The clusters of describing words (the PCs) for vacuum cleaners and washing machines are smaller than the lexicon of 62 words and they differ from each other. The chart of a vacuum cleaner ASP in Figure 8 shows the descriptive words that make up each PC. We can see that most of the words are related to each other, giving us a sense of the meaning of each PC. Each PC gets a 'score,' indicating the strength of that PC in contributing to the ASP for that product. The sample ASP for a washing machine in Figure 9 shows the effect on the ASP for a particular defect – a noisy motor vs. a noisy transmission (Sounds K,M).[1] The PCs for the vacuum cleaner sounds are different from those for the washing machine, confirming what we already know: the character of the sounds depends on the product.

A consumer jury was subsequently presented with these same product sounds and asked to judge them on acceptability (Figure 10). Since we have the ASP for each sound, we can attempt to correlate differences in ASP with the SQ. A linear transformation between the SQ rating by the jury and the ASP as determined by the expert panel allows us to predict the SQ once the ASP is determined.

The second step in the process is to find a relationship between physical metrics and the ASPs. If a dimension of the sound relates to descriptors like 'shrill' or 'tinny,' we can reasonably expect it to correlate with higher frequency components in the sound. By using a set of metrics partially derived on the basis of such correlations, we derive a second transformation between the "metrics profile" or MP and the ASPs. The MP can then be determined in the design facility and used to predict the ASP, which in turn is used to predict the SQ.

There are a number of "sound quality metrics" in use by industry at present. Examples include loudness, sharpness, fluctuation strength, harshness, roughness and annoyance. We have chosen to use a simpler set of nine metrics based on third octave spectra and modulation of the sounds. However, one can add any metrics to the list that one wishes and use principal component analysis to determine the combinations of metrics that best predict the ASPs.

The MP for the vacuum cleaner sounds that correspond to the ASPs shown in Figure 8 are presented in Figure 11. The MP that corresponds to the ASPs for the washing machine sounds in Figure 9 is shown in Figure 12. In all cases, we can see that a distinct difference in the ASP is accompanied by a distinct change in the MP that is needed for the desired correlation between the MP and the ASP. We have, therefore, accomplished the mapping from design to perception using the ASP as intermediary, as shown in Figure 13.

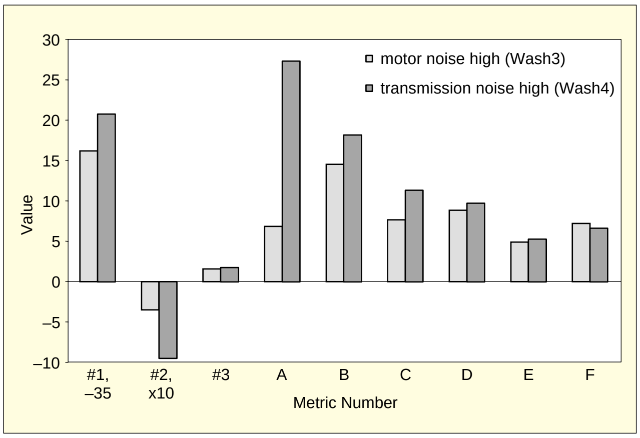

Figure 12. Comparison of physical metrics for two washing machine sounds.

Other Algorithms (Metrics) for SQ

As I have indicated, we have found that certain metrics can be an intermediary between SQ and design through their correlation with ASPs. Some fairly new "sound quality metrics" with names like 'roughness' and 'sharpness' are available in modern instrumentation systems that are widely dispersed, particularly within the automotive industry. It appears that many users hope these metrics can form a direct link between design and SQ. I am not convinced that this is the case. Does the Roughness algorithm capture what I perceive when I say, "That engine sounds rough."?

As an illustration, consider the following sounds. The first is a recording of a piano piece by Bach (Sound N).[1] This piece is then played backward, note by note, and recorded. The signal is then reversed so that the notes are in the right order, but individual piano tones are reversed. The second sound (Sound O)[1] is very pleasant, but not at all acceptable as the sound of a piano. We could certainly construct a metric that would tell them apart but none of the standard metrics would be able to tell the difference.

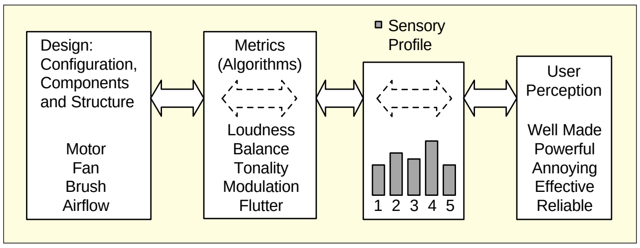

Figure 13. Mapping from design to perception.

So, in acoustics we have a better situation than they do in Sensory Testing for taste, touch and flavor. We can in fact record very precisely what is presented to our ears. But the cognitive processes that convert sounds to feelings and intelligence are not captured by our calculations. Metrics are at best a bridge between the sound pressure signal and our evaluations of SQ for products. We will continue to need people to listen to and evaluate product sounds. And, they will need to mind their (AS)Ps and their (S)Qs.

References

1. All sounds can be found as *.wav files on S&V's website on the "Current Issue" page under the 'Downloads' section, www.SandV.com.
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