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SOUND DESIGN OF MACHINES FROM A MUSICAL PERSPECTIVE

Hugo Fastl
AG Technische Akustik, MMK, TU München,
Arcisstr. 21, D-80333 München, Germany
E-mail: Fastl@mmk.ei.tum.de

ABSTRACT

In this paper, relations between musical acoustics and sound quality engineering are displayed. First, the concept of musical consonance proposed by Terhardt, based on the seminal classic work of Helmholtz is discussed. In particular, the view of Helmholtz on modern psychoacoustic magnitudes important in sound quality design like fluctuation strength and roughness is illustrated. The application of Terhardt's concept of sensory pleasantness in sound quality engineering is discussed, and advantages and disadvantages are shown. The concept of virtual pitch, i.e. a pitch sensation which has no direct correspondence in the spectrum, is traced back to the concept of "basse fondamentale" put forward by Rameau in the 18th century. Characteristics of musical keys as advocated by Kirnberger and Schubart are displayed in view of the sound quality of the interior sound of passenger cars. Musical dynamics from *ppp* to *fff* are contrasted to current category scales for loudness scaling and the relations of loudness and tone color. Finally, examples of audio-visual interactions in speech and music as well as sound quality rating are given.

CONCEPT OF MUSICAL CONSONANCE

The concept of musical consonance as advocated by Terhardt (1984) is illustrated in figure 1. Musical consonance depends on two features, namely harmony and sensory consonance.

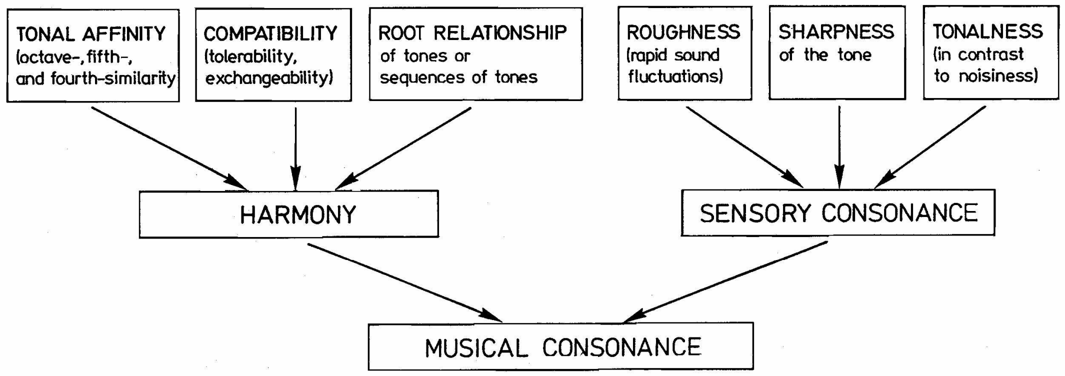


Figure 1: Concept of musical consonance according to Terhardt (1984).

The concept of harmony was developed for musical sounds, whereas the concept of sensory consonance can be applied not only to musical sounds, but to all categories of sounds, e.g. sounds usual in sound quality engineering. Nevertheless, the concept of harmony also can have an impact with respect to sound quality. A basic result of the work of Helmholtz (1863) was his discovery that the hearing sensation roughness strongly influences sensory consonance. In modern terminology (e.g. Zwicker and Fastl 1999), the concept of Helmholtz would read that fluctuation strength and roughness are mainly based on interactions of spectral components of sounds. Figure 2 gives an illustration of the concept of Helmholtz in musical notation.

Figure 2: Interaction of spectral components in musical notation according to Helmholtz (1863).

In figure 2, the unfilled notes represent the sounds played e.g. on a piano. The filled notes indicate harmonics. In example 1, the musical interval of an octave is displayed. The sounds played are c_2 and c_3 as indicated by unfilled notes. In addition to c_2 the harmonic c_3 (filled note) is audible, which gives a perfect match to the presented note c_3. This means that in the musical concept, the octave c_2-c_3 represents a perfect consonance without beats, because the second harmonic of c_2 (c_3) is identical to the higher note c_3. In contrast, example 2, which consists of the notes c_2 and b_2 represents a dissonance, because the presented note b_2 is a semitone apart from the second harmonic c_3 of the note c_2. A similar argument holds for example 3. Examples 4 and 5 of Helmholtz again show consonant intervals which is easily seen in example 5: the notes played are d_4 and a_4 which form the musical interval of a fifth. The second harmonic of d_4 is d_5 and the third harmonic a_5, whereas the second harmonic of a_4 is a_5. Since the second harmonic of a_4 and the third harmonic of d_4 coincide, the interval of a fifth is considered to be a consonance.

This reasoning is described in more detail in figure 3 from Helmholtz, where he illustrates the roughness of different musical intervals.

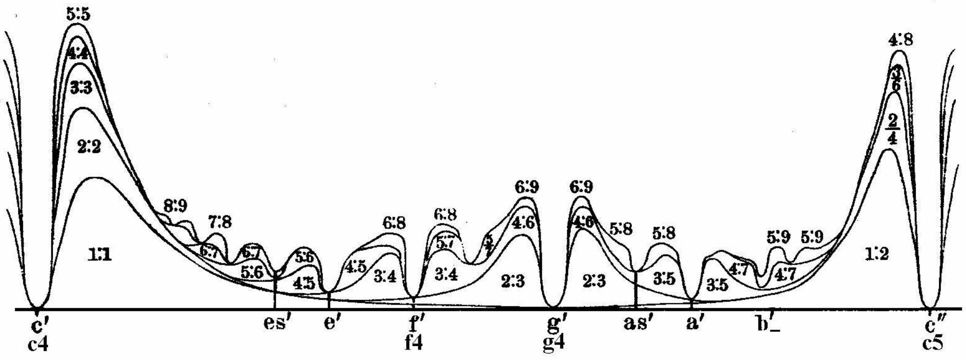


Figure 3: Roughness of different musical intervals according to Helmholtz (1863).

The intervals considered always start with c_4, and the magnitude of the peaks indicates the magnitude of the roughness of the respective interval. As is easily seen in figure 3, the octave namely the interval c_4-c_5 represents a perfect consonance and no roughness is visible. Also for the fifth c_4-g_4, Helmholtz displays no roughness values. On the contrary, the roughness of musical intervals reaches according to Helmholtz a maximum for one musical semitone (c_4-cis_4) or for eleven semitones (c_4-b_4).

The results displayed in figure 3 clearly show that the concept of musical consonance is based on the absence of the psychoacoustic magnitude roughness, which we use these days in sound quality engineering. In line with classic music theory dating back to 500 BC of Pythagoras, the musical intervals of octave, fifth and fourth with frequency ratios of 1:2, 2:3, and 3:4 are considered as perfect consonances because they show no fluctuation strength or roughness.

Based on the classic findings by Helmholtz (1863), Terhardt and Stoll (1981) proposed the concept of sensory pleasantness which is illustrated in figure 4.

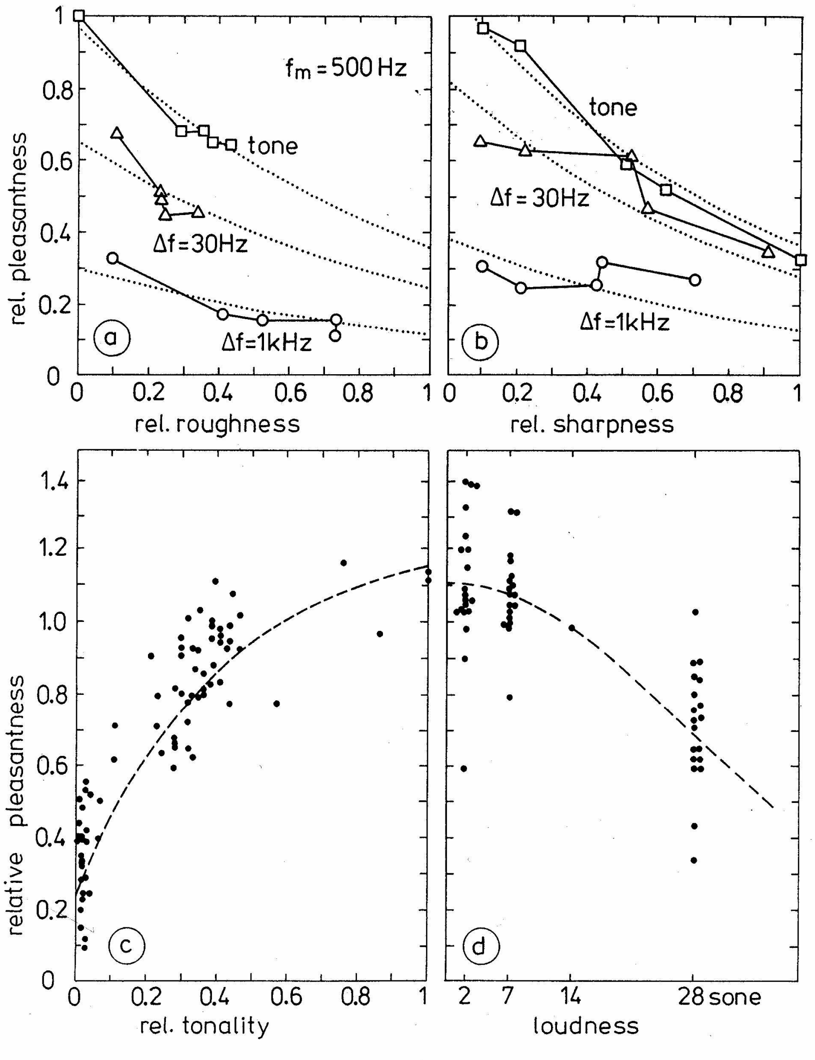


Figure 4: Concept of sensory pleasantness according to Terhardt and Stoll (1981).

As expected from the classic works of music theory, sensory pleasantness decreases with increasing roughness (figure 4a). Also in line with data from Helmholtz (1863), figure 4b shows that sensory pleasantness decreases with increasing sharpness. Panels 4d and 4c indicate that sensory pleasantness decreases with increasing loudness, but increases with increasing tonality.

While the results displayed in panels 4a, 4b, and 4d are well known in sound engineering and sound quality design, the results displayed in panel 4c have to be considered in more detail. It is clear that in a musical context, as displayed in figure 1, sensory consonance and hence sensory pleasantness increases with the tonal character of a sound. However, in sound engineering, exactly the opposite behavior may occur! In many standards, tonal components of sounds are "punished" by tone penalties. For example, in the German standard for noise immissions from industrial noise (TA Lärm), for sounds with clearly audible tonal components, a tone correction of up to 6 dB is added to the measured A-weighted level, and calculations for the tone corrections are proposed in the German standard DIN 45681. This means that in a musical context, tonal components usually have a positive impact, whereas in sound engineering generally tonal components should be avoided.

An interesting example in this context comes from Japan: A manufacturer of needle printers controlled the sequence of the needles in such a way that the printer played well known tunes. In the beginning, when this feature was introduced, it was very welcome by the users because of its novelty. However, after few days it can be pretty annoying, if a printer plays the same tunes over and over again.

ROOTS OF MUSICAL CHORDS AND VIRTUAL PITCH

It is well known in music theory, that musical chords represent a specific tonality, frequently called the "root" of the chord. This means that the "root" represents a suitable bass note and further can be responsible for the tonality of a piece of music, e.g. that a tune is written in C-major. As displayed in figure 1, this relationship belongs to the concept of harmony. It dates back to the 18th century and is described in great detail by the famous French music theorist Rameau (1750). In musical terms, the notes displayed in figure 5 illustrate that the chord g c e has the "meaning" of C-major. In music theory, this is explained that the notes g_4, c_5, and e_5 are considered to be the third, fourth, and fifth harmonic of a common root. As displayed in figure 5, the first harmonic which fits the chord displayed by filled notes is the unfilled note c_3, and the second harmonic is the unfilled note c_4. The frequencies of these notes form the ratio 1:2:3:4:5 and hence correspond to the musical intervals octave, fifth, fourth, and major third.

Figure 5: Illustration of the concept of “basse fondamentale” of Rameau (1750)

As we have seen, up to the fourth, since ancient times these intervals are considered to be consonant. However, the major third got more and more acceptance as a consonant interval in the 17th century, but was a little suspect to older music theorists like Pythagoras.

Rameau's (1750) concept of "basse fondamentale" has its modern counterpart in the virtual pitch theory of Terhardt (1974) which is illustrated in figure 6.

In the example displayed in figure 6, a harmonic complex tone with a basic frequency of 200 Hz is considered, from which the first two harmonics (200 Hz and 400 Hz) are removed. In essence, the concept of virtual pitch predicts that from the spectral pitches of each harmonic, subharmonics are calculated by integer ratios (1:1, 1:2, 1:3, 1:4, and so forth). The amount of coincident calculated subharmonics gives an indication of the virtual pitch perceived. As becomes clear from the example given in figure 6, virtual pitch has some ambiguity: Terhardt's model calculates the virtual pitch of the incomplete complex harmonic tone near 200 Hz. But also pitches one octave lower or one octave higher are candidates. This ambiguity is in line with the musical concept shown in figure 5, because the "root" of the chord displayed is represented by c_3, but c_4 is also possible.

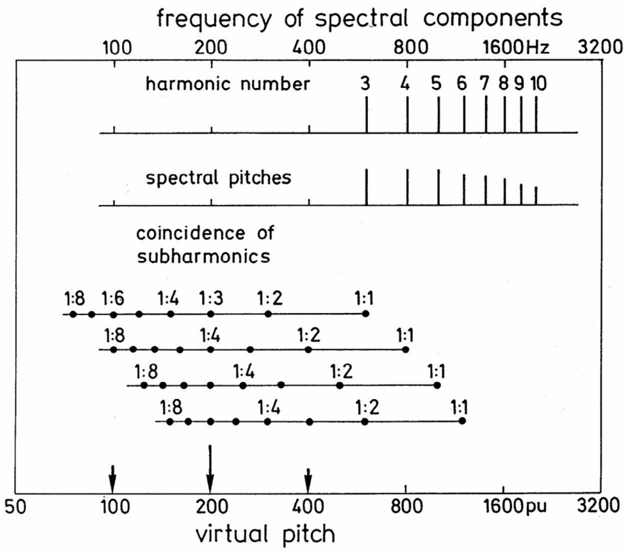


Figure 6: Illustration of the concept of virtual pitch of Terhardt (1974).

For sound quality engineering the concept of virtual pitch which is based on the musical concept of harmony plays an important role: the sound of a product can produce a pitch sensation in a frequency region where no spectral components are present! When assessing sound quality by physical means like spectral analysis, it always has to be kept in mind that audible tonal components can be virtual pitches, which show up in the spectrum only by higher harmonics.

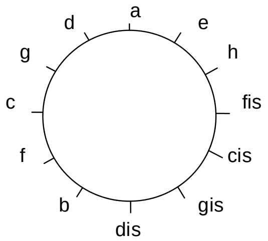
CHARACTER OF MUSICAL KEYS

It is a long standing debate, whether musical keys can represent a specific character. In particular Kirnberger (1782) and Schubart (1806) related different keys to different emotions or moods. Experiments by Kunkel (1877) as well as our own experience showed that with equal temperament it is more or less impossible to correlate different emotions with different musical keys. However, in well tempered intonations, i.e. a tuning put forward in particular by Werckmeister (1702) and used by the famous composer Johann Sebastian Bach, characteristics of musical keys may be perceived by experts.

Since a famous German manufacturer of passenger cars insists that a luxury car has to be tuned in minor and not in major, figure 7 gives (more as curiosity) the characteristics of minor keys in the original language German.

To cut a long story short, from all the keys given in figure 7, only the first two namely a-minor and e-minor may be useful for sound design because all the other keys represent feelings of sadness and despair. However, according to the results displayed in figure 7, a-minor should have a religious, feminine character, and e-minor should be related to the love of a naive girl.

Although this author has studied music, it is not easy to detect the character of these keys in minor, and in particular it seems to be the secret of the German car manufacturer, how to tune the interior sound of a car in a minor key, and whether this is then a-minor or e-minor.



Charakteristik der Molltonarten
nach Schubart

1. Klasse *(Weiblichkeit und Sanftmut)*	**a - Moll**	*fromme Weiblichkeit und Weichheit des Charakters*
	e - Moll	*naive, weibliche unschuldige Liebeserklärung vergleichbar mit einem Mädchen, weiß gekleidet, mit einer rosaroten Schleife am Busen*
	h - Moll	*schwermütige Weiblichkeit, die Spleen und Dünste brütet*
	d - Moll	*Ton der Geduld, der stillen Erwartung seines Schicksals und der Ergebung in die göttliche Fügung*
2. Klasse *(bedrückende Traurigkeit)*	**fis - Moll**	*finsterer Ton*
	cis - Moll	*Bußklage, Seufzer der unbefriedigten Freundschaft und Liebe*
	gis - Moll	*Griesgram, gepreßtes Herz bis zum Ersticken; Jammerklage, die im Doppelkreuz hinseufzt; schwerer Kampf, mit einem Wort, alles was mühsam durchdringt ist dieses Tons Farbe*
	es - Moll	*Empfindungen der Bangigkeit als aller tiefsten Seelendrangs; der hinbrütenden Verzweiflung, der schwärzesten Schwermut, der düstersten Seelenverfassung*
3. Klasse *(hoffnungslose Traurigkeit)*	**g - Moll**	*Mißvergnügen, Unbehaglichkeit, Groll, Unlust*
	c - Moll	*Klage der unglücklichen Liebe*
	f - Moll	*tiefe Schwermut, Leichenklage, Jammergeächz und grabverlangende Sehnsucht*
	b - Moll	*Moquerien gegen Gott und die Welt, Vorbereitung zum Selbstmord*

Figure 7: Characteristics of musical keys in minor according to Schubart (1806)

MUSICAL DYNAMICS

As is well known from music theory, musical dynamics ranges between very soft (pianissimo *pp*) and very loud (fortissimo *ff*). For extreme values of loudness the musical notations piano pianissimo (*ppp*) and forte fortissimo (*fff*) are used. Figure 8 enables a comparison of musical dynamics with category scales frequently used for sound quality engineering.

pp	***p***	***mf***	***f***	***ff***
very soft	soft	neither soft nor loud	loud	very loud

ppp	***pp***	***p***	***mf***	***f***	***ff***	***fff***
extremely soft	very soft	soft	neither soft nor loud	loud	very loud	extremely loud

Figure 8: Musical dynamics and category scales.

The upper panel shows a five step category scale, the lower panel a seven step category scale. It is interesting to note that there is good correspondence between the symbols of musical dynamics and loudness rating. However, for the middle category (mezzoforte *mf* in musical notation), the interpretation is a little different in sound quality engineering and musical acoustics: in sound engineering, the category neither soft nor loud is just in the middle between the category soft on the one hand, and the category loud on the other hand. In musical notation however, mezzoforte means a little loud or half loud, and therefore is not centered between soft and loud, but closer to loud. Despite these small differences, category scalings with five step scales or seven step scales have proven successful in sound quality engineering.

When talking about loudness, two important influences for musical acoustics as well as sound engineering have to be discussed. As an example, figure 9 shows the loudness patterns for the musical note f_4 played by a horn in a reverberant chamber at the musical dynamics pianissimo *pp* or fortissimo *ff*. As becomes clear from the loudness values N in sone as well as the areas of the loudness distributions, for fortissimo the loudness is about a factor of eight larger than the loudness for pianissimo. However, in addition, a considerable shift in spectral distribution can be noticed. While for pianissimo the first harmonic near 4 Bark is dominant, for fortissimo the second harmonic near 8 Bark takes over. This is related to the blaring sound of a horn when played at fortissimo. Similar interactions of loudness and tone color are well known from sound quality engineering. Therefore, for modifications not only the differences in level, but also differences in spectral distribution have to be taken into account. Loudness patterns as displayed in figure 9 represent a valuable tool to evaluate differences in loudness, and at the same time in tone color.

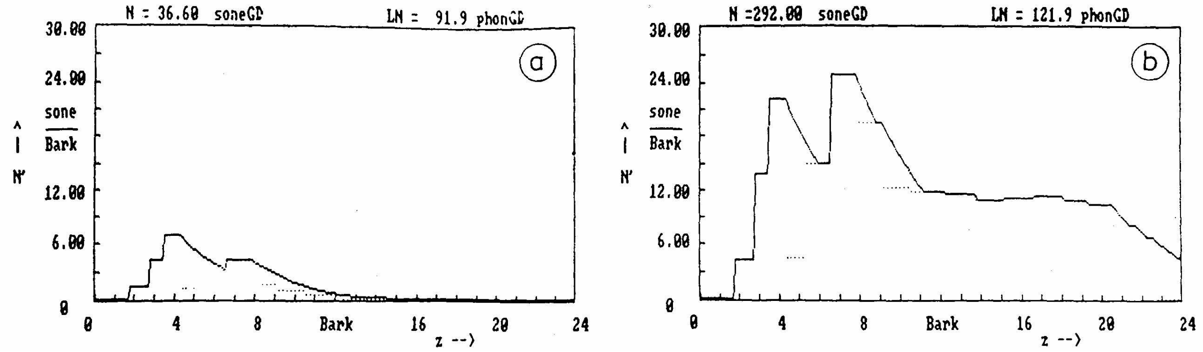


Figure 9: Loudness patterns for the note f_4 played by a horn in a reverberant chamber at the musical dynamics pianissimo *pp* (a) or fortissimo *ff* (b).

Along these lines, figure 10 again illustrates that at <u>same</u> level, for sounds with different spectral distribution, the perceived loudness can differ considerably.

For the same level of 85 dB(A), the left panel shows the loudness pattern of a piccolo flute, the right panel of a pipe organ with full registers. Because of the larger bandwidth of the organ sound, at same level, the perceived loudness is about a factor of two larger. These effects of bandwidth of the sound source are well known in music and assessed by conductors as well as sound recording engineers. They also can play an important part in sound engineering and sound quality design.

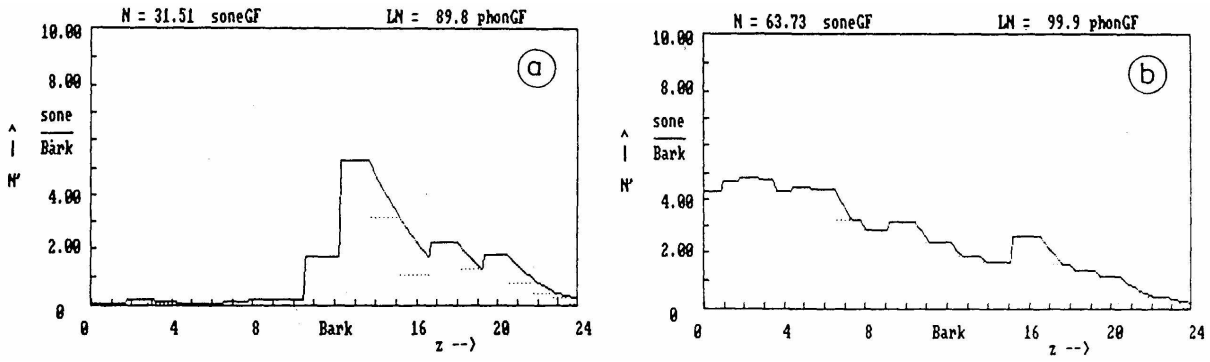


Figure 10: Loudness pattern of a piccolo flute (a) and a pipe organ (b) at same A-weighted level of 85 dB(A).

AUDIO-VISUAL INTERACTIONS

The last example illustrates audiovisual interactions which can play a role both in musical acoustics and sound quality engineering. Figure 11 shows a simplified floor plan of a concert hall and its stage. A speaker S is placed on the stage, and speech is recorded at different places 1, 2, and 3 in the concert hall.

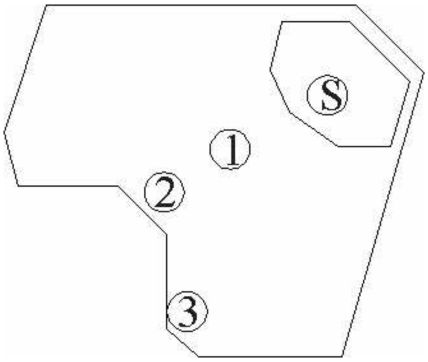


Figure 11: Schematic plan of the ground floor of a concert hall with indications of the source S and three positions 1 through 3 of the receiver.

The rating of speech quality is done either by just presenting the sound recorded at the places 1, 2, and 3, or by additional presentation of the correlated visual image. The corresponding ratings of speech quality are given in figure 12. Unfilled symbols represent ratings with acoustic presentation only, filled symbols indicate ratings for acoustic plus visual presentation.

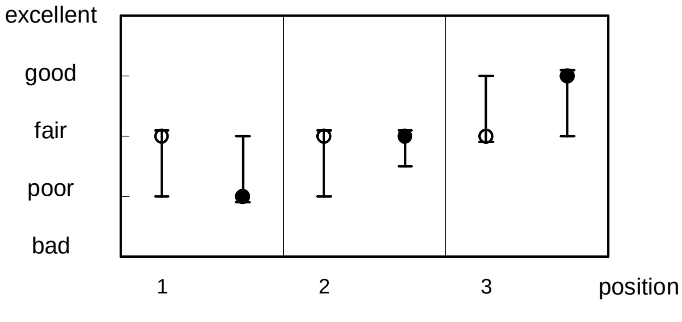


Figure 12: Rating of speech quality in a concert hall at positions 1, 2, and 3 for acoustic presentation alone (unfilled symbols) or acoustic plus visual presentation (filled symbols).

The data displayed in figure 12 show that for acoustic presentation alone, speech quality is rated to be fair. If however, in addition to the acoustic presentation a photo of the situation in the concert hall is presented to the subjects, despite identical acoustic input, the rating may be influenced. At position 1, with the additional presentation of the visual image, the rating gets poorer. At position 2, the visual image has no influence on the rating, whereas at position 3, the rating improves with the visual image. These results may be interpreted as follows: In position 1, the source is very close to the receiver, and therefore with the visual image the subject expects a very clear sound which does not occur for speech in a concert hall with a reverberation time of about two seconds. At position 2, the visual image shows a larger distance to the source, and therefore the subjects seem to accept some compromise with respect to sound quality. Interestingly, at position 3, the presentation of the visual image improves the rating. This might be due to the fact that in the visual image, the subject realizes a large distance between source and receiver, and feels that - given that adverse situation - the speech quality can be considered as good.

Another effect of audio-visual interaction is well known by sound recording engineers: If a musician hits inadvertently with his instrument his music stand, the audience in the concert hall hardly notices the related impulsive sound. However, when recorded on a CD, the same noise definitely is unacceptable. Since in the concert hall, the visual information can explain the reason for the noise, it remains largely unnoticed.

Similar audio-visual interactions were reported by Suzuki et al. (2000) with respect to the sound quality of noises. They could show that when the sound of white noise is combined with the image of a waterfall, the rating of the sound quality improves. Likewise, Hashimoto and Hatano (2001) demonstrated that visual images can influence the rating of car sounds considerably: In an experiment with semantic differential, they measured the rating of the interior sound of passenger cars for acoustic presentation alone, or for the combination of acoustic plus visual presentation of the moving car. Compared to acoustic presentation alone, the rating of the adjectives “pleasant” or “quiet” improved by one step of the seven step scale with the presentation of the corresponding visual image. For many adjective pairs, the improvement in rating with the addition of the visual image corresponded to a decrease in sound pressure level by as much as 10 dB! Patsouras and Böhm (2002) reported that the influence of a visual input on the rating of interior sounds of cars increased with the complexity of the visual presentation. In addition, Patsouras et al. (2002) reported that the loudness rating for train noise also may be influenced by the additional presentation of visual images.

CONCLUSION

The few examples described in this paper indicate that musical acoustics and sound quality design have several aspects in common. In addition, it is interesting to note that tools which nowadays we use in sound engineering, first were developed for musical acoustics. For example, dummy head recordings were used in the 1960s for evaluations of the sound quality of concert halls. Despite the fact that dummy heads still are used in a musical context, the majority of instruments these days is used in the context of sound engineering. On the other hand, the analysis of radiation patterns has gone back and forth between musical acoustics and sound quality design. In the 18th century, Chladni (1787) illustrated the radiation patterns of musical instruments by putting on them small seeds, showing the distribution of regions with large or small vibration. These days, laser vibrometers, which enable a very detailed analysis of the vibration pattern of products, are very helpful tools for sound quality engineering. However, they are also used to measure the vibration patterns of musical instruments. Despite all this modern equipment, the mystery e.g. of the superb sound quality of old Italian violins has not yet been revealed. This means that although we have achieved a high standard both in musical acoustics and sound quality design, many open questions still wait to be solved.

ACKNOWLEDGEMENTS

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