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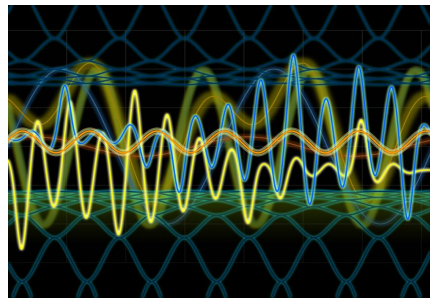
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Design Principles of Pipe Organ Mixtures – viewed from a psychoacoustic Position

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The term "Mixture" refers to a compound stop of high-pitched ranks adding brilliance and loudness to the pipe organ sound. As Mixture stops and their sound have been refined over centuries, one can expect to find a set of correlating psychoacoustic parameters in their long-term average sound spectra representing a well-balanced sound. Mixture stops generate some pitch salience at their fundamental pitch and the participating ranks partly merge with each other. However, Parncutt's theory of harmony shows that Mixtures do not aim at maximum pitch salience at unison pitch. The pitch heights of the individual ranks contributing to a Mixture stop fall into separate critical bands in most cases. Consequently, Mixtures increase the loudness while avoiding acoustical roughness between their neighbored pitches. This explains the selection of certain pitches from the harmonic series. Finally, the common practice of introducing breakpoints into the ranks contributing to a Mixture adjusts the course of their acoustic brightness over the key compass. It reduces from bass to treble in a similar manner, as it is the case in bright brass instruments or as the trumpet stop on a pipe organ does. This sound might thus have been influenced the development of pipe organ Mixtures.

1. INTRODUCTION

The term *Mixture* refers to a pipe organ stop, in which more than one rank of organ pipes with the ranks tuned to different pitch heights, are grouped together. Pressing a single key on the keyboard generates a sounding chord or at least a dyad rather than just a single note. The pitch heights in Mixtures are most frequently octaves and perfect fifths or other intervals of the harmonic series of a common fundamental pitch. Historically, Mixture stops developed around the year 1500 in Northern German organ building¹. The pipes of the top notes of Mixtures become eventually too short to manufacture and difficult to tune. Thus, the involved ranks must either cease to exist from a certain pitch onwards or they have to break back (e.g. when the pitch jumps down one octave) – the latter appeared around 1500¹. Nowadays, organ builders follow certain design rules for Mixture stops, which have evolved from experience and there are schemes for the pitch heights at which the contributing ranks break back. Presuming that these rules are based on centuries of experimenting while pursuing tonal improvement (although the preference of the tonal ideal has changed over time) one could possibly correlate them to psychoacoustic parameters and correlate them with optimized sonority. The following three chapters provide insights into three different aspects, which are promising candidates: The first is pitch salience at the fundamental pitch, the second is how the pitch heights of the ranks within a Mixture relate to critical bands. Finally, this investigation will tackle the question how the tonal sharpness (on a scale from “dull” to “sharp”) changes when ranks break back. All these investigations rely on models with simplified assumptions.

2. PITCH SALIENCE AT THE FUNDAMENTAL

A. WHY TO INVESTIGATE THIS PARAMETER

Since the pitches of the different ranks within a Mixture are all part of the harmonic spectrum of a common fundamental, they enhance the pitch salience of this fundamental. Since this effect is due to virtual pitch (a pitch percept generated by the auditory system despite the absence of acoustical power at the fundamental), it does not require any physical sound source at the frequency of the fundamental itself. One could thus imagine that Mixtures are designed for maximum pitch salience at the fundamental and that they aim for best blending of their ranks. To investigate if this is the case, the pitch saliences and the multiplicities of two different Mixtures are calculated using long-term average sound spectra (LTAS) of an OPEN FLUTE and an OPEN DIAPASON rank.

B. A SIMPLIFIED SOUND SPECTRA MODEL

Sound spectra of organ pipes depend on so many parameters (pipe dimensions, wind pressure etc.) that their calculations based on a physical model remain approximations. Thus, a simplified description of the LTAS with a couple of free parameters must suffice for this approach. According to a related study², a reasonable approximation for the LTAS of organ pipes is given by the harmonic partials, whose sound spectra level L_n lies within a spectral envelope bordered by a straight-line approach. The sound pressure levels (SPL) L_n at the n -th harmonic partial are:

$$L_n = \Delta L_G + \begin{cases} L_1 + A \cdot \Delta o, & \text{if } n \text{ is odd and } n \leq n_{ip} \\ \Delta L + L_1 + A \cdot \Delta o, & \text{else} \end{cases} \quad (1)$$

The first term in Eq. (1) is due to the end correction of the pipe reducing the SPL at the partial number n_G , an effect approximated by the Gaussian function multiplied by negative factor L_G as formulated in Eq. (2):

$$\Delta L_G = L_G \cdot \exp\left(\frac{(n-n_G)^2}{2\sigma^2}\right) \quad (2)$$

The parameters L_1 and ΔL in Eq. (1) are the SPL at the fundamental ($n = 1$) and a SPL difference, respectively. With increasing pitch distance from the fundamental, the SPL change yielding a simplified LTAS. The pitch distance Δo measured in octaves or – alternatively – in semitones, Δp , is required to calculate the last factor in Eq. (1) keeping in mind that an octave equals twelve semitones: $\Delta o = \Delta p / 12 = (p_n - p_1) / 12$, where p_n and p_1 indicate the pitch categories of the n -th partial and the fundamental, respectively. The factor A creates

two ranges in the LTAS with different slopes s_{R1} and s_{R2} according to Eq. (3). It ensures a smooth transition between range 1 and 2 with the aid of the arcus tangent function, whose calculation requires the pitch distances Δo and Δo_{ip} , of which the latter measures from the fundamental to the border between the two ranges.

$$A = \frac{1}{p_n - p_1} \cdot \sum_{p_1}^{p_n} ((1 - a) \cdot s_{R1} + a \cdot s_{R2}) \quad \text{with} \quad a = \frac{1}{\pi} \cdot \arctan\{s_a \cdot (2^{\Delta o} - 2^{\Delta o_{ip}})\} + \frac{1}{2} \quad (3)$$

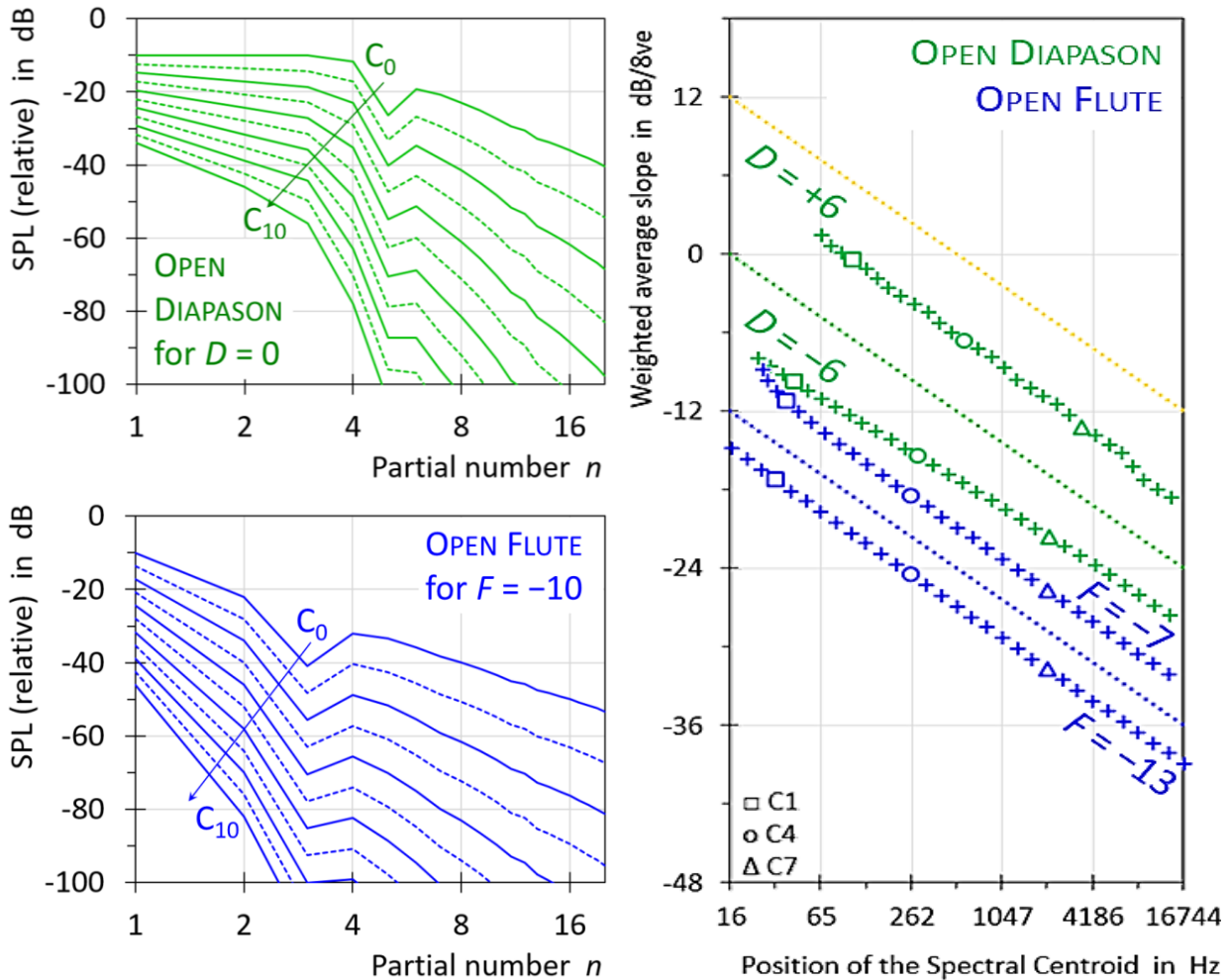


Figure 1. LTAS (left) and timbre chart (right) for the OPEN FLUTE and the OPEN DIAPASON at different pitches.

A detailed description of the LTAS model is the subject of an accompanying article². Table 1 shows the parameters believed to represent the pitch-dependent LTAS for a typical OPEN FLUTE and a typical OPEN DIAPASON rank. Six of seven parameters for each rank are set to constant values. The remaining variable influences the slope parameter s_{R1} , abbreviated by F and by D for the OPEN FLUTE and for the OPEN DIAPASON, respectively. Fig. 1 depicts the envelope functions of the LTAS of these two ranks for $F = -10$ and $D = 0$. Different values of D and F correspond to the transition of the tonal timbre between the families of organ tone from “flutey” for the OPEN FLUTE to “stringy” while crossing the typical tonal range for an OPEN DIAPASON. The parameters for these two ranks represent parallel straight lines in the timbre charts (Fig. 1), in which the courses for typical representatives of an OPEN FLUTE (for $F = -10$), an OPEN DIAPASON (for $D = 0$), and a STRING are highlighted using blue, green, and yellow dotted lines, respectively. These dotted lines are best guesses for these three ranks from a data analysis of the LTAS of many different organ pipes from various ranks².

Table 1. Parameters for the LTAS for the ranks OPEN FLUTE and OPEN DIAPASON to simulate different Mixtures.

Parameter	Meaning	OPEN FLUTE	OPEN DIAPASON
ΔL_G	SPL difference at n_G	$\Delta L_G = -15$ dB	$\Delta L_G = -12$ dB
n_G	Max. of the Gaussian function	$n_G = 3.0$	$n_G = 5.0$
σ	Std. dev. of the Gaussian function	$\sigma = 0.5$	$\sigma = 0.5$
ΔL	SPL difference	$\Delta L = 0$	$\Delta L = 0$
L_1	SPL of the fundamental ($n = 1$)	$L_1 = (90 - 0.30 \cdot p)$ dB	$L_1 = (90 - 0.20 \cdot p)$ dB
s_{R1}	Slope in range 1 in dB/8ve	$s_{R1} = (F - 0.20 \cdot p)$ dB/8ve	$s_{R1} = (D - 0.10 \cdot p)$ dB/8ve
s_{R2}	Slope in range 2 in dB/8ve	$s_{R2} = \text{n.a.}$	$s_{R2} = (-13 - 0.30 \cdot p)$ dB/8ve
s_a	“Steepness” of the arc tangent	$s_a = 500$	$s_a = 500$
Δo_{ip}	Position for the transition between range 1 and 2 n_{ip}	$\Delta o_{ip} = \infty$	$\Delta o_{ip} = \log_2(24 - 0.05 \cdot p)$

Typical values for the slopes of the two ranks in range 1 are obtained by setting $F = -10$ and D equal to zero. The OPEN FLUTE requires one slope parameter (s_{R1}), only, i.e. there is no range 2 in its model.

C. CALCULATING PITCH SALIENCE

Parncutt’s psychoacoustic model³ describes the perception of tones and allows for calculating pitch salience $S(p)$, a quantity that expresses how salient the different pitch heights p evoked by a tone are perceived³. The model requires sound spectra in semitone steps, created with Eq. (1), Eq. (2) and Eq. (3). These spectra served as input data for two different Mixtures: a four-rank CORNET and a four-rank Mixture, referred to as ACUTA (Table 2). This work uses the updated equations⁴ of Parncutt’s model as they provide a better approximation for the hearing threshold⁴ and consider equivalent rectangular bands (ERB) to estimate mutual masking; in addition, a more recent critical-band rate⁵ formula is included. There are three free parameters in this model:

$k_M = 12 \dots 18$ dB/erb (used to describe stronger ($k_M = 12$) or slighter ($k_M = 18$) mutual masking), $k_T = 1 \dots 10$ (to adjust for holistic ($k_T = 1$) to analytic ($k_T = 10$) listening). The given ranges represent typical values derived from psychoacoustical data⁴. A third parameter was kept constant at $k_S = 0.5$ (a typical value for way in between holistic and analytical listening⁴). It is important to understand that the calculated value $S(p)$ depends on the choice of the values assigned to these three parameters.

This pitch salience model serves for two numerical experiments: The first shall answer the question whether the two Mixtures in Table 2, the CORNET and the ACUTA, do indeed enhance the pitch salience at the fundamental pitch (C_4), i.e. $S(p = 48)$, in general written as $S(\Delta o = 0)$. Therefor a numerical least-squares’ algorithm tried to maximize the value $S(\Delta o = 0)$ by varying the values F and D , while all other parameters were set to the values in Table 1. This corresponds to the experimental task of constructing a Mixture by combining the pitches given in Table 2 while using one rank of pipes, either an OPEN FLUTE or an OPEN DIAPASON. The SPL of the pipes and their tonal timbre (“flutey” – “stringy”) follow from the values given in Table 1. The different values for F or D translate in the fact that each rank is provided in several variants of tonal timbre. If organ builders aims at achieving maximum pitch salience $S(\Delta o = 0)$, then the numerical refinement should yield realistic values for F or D – “realistic” meaning that these Mixtures can be built from ordinary ranks of pipes as parametrized by the values in Table 1. As the CORNET typically consists of OPEN FLUTE ranks and the ACUTA normally contains OPEN DIAPASON ranks, the numerical results might eventually confirm these preferences. To cover different kinds of listeners with these numerical refinements the free parameters in Parncutt’s model were varied within the extended typical ranges⁴ as follows: $k_M = (12, 15, 18)$ dB/erb, $k_T = 1, 3, 10$ and $k_S = 0.5$.

Table 2. Composition of two selected Mixtures, both based on pitch C_4 .

CORNET IV	Partial no. m	Pitch	Δp	Δo		ACUTA IV	Partial no. m	Pitch	Δp	Δo
	2	C_5	12	1			2	C_5	12	1
	3	G_5	19	$1 \frac{7}{12}$			3	G_5	19	$1 \frac{7}{12}$
	4	C_6	24	2			4	C_6	24	2
	5	E_6	28	$2 \frac{4}{12}$			6	G_6	31	$2 \frac{7}{12}$

In the second numerical experiment the values F and D of the two Mixtures in Table 2 were kept constant and the SPL of the three highest ranks were allowed to deviate by $\Delta L_{l,m}$ from the values L_l as calculated by Eq. (1) using the parameters in Table 1. Again, the refinement criterion was maximum pitch salience at fundamental pitch ($p = 48$, i.e. $\Delta o = 0$). This corresponds to working with a rank of pipes with a certain timbre quality (e.g. a “flutey” or a “stringy” OPEN DIAPASON), and to adjust the SPL of the individual pipes in relation to each other until $S(\Delta o = 0)$ becomes maximal. The CORNET and the ACUTA were constructed to either contain only OPEN FLUTE or OPEN DIAPASON pipes. The free parameters in Parncutt’s model were set to the typical values⁴ $k_M = 12$ dB/erb, $k_T = 3$ and $k_S = 0.5$.

D. RESULTS

To provide a comparison to the forthcoming simulations, Fig. 2 depicts pitch salience charts for the sound spectra of the two ranks listed in Table 1 for $F = -10$ and $D = 0$, each for a single note at C_5 . Note the pitch salience below C_5 , with a local maximum at C_4 , i.e. one octave below. Keep in mind that even a pure tone evokes some pitch salience at the sub-octave pitch and other partials of the sub-harmonic series³. The aim of the following two numerical experiments is to increase the pitch salience at C_4 by adding pipes of the same rank at the other pitch heights given in Table 2.

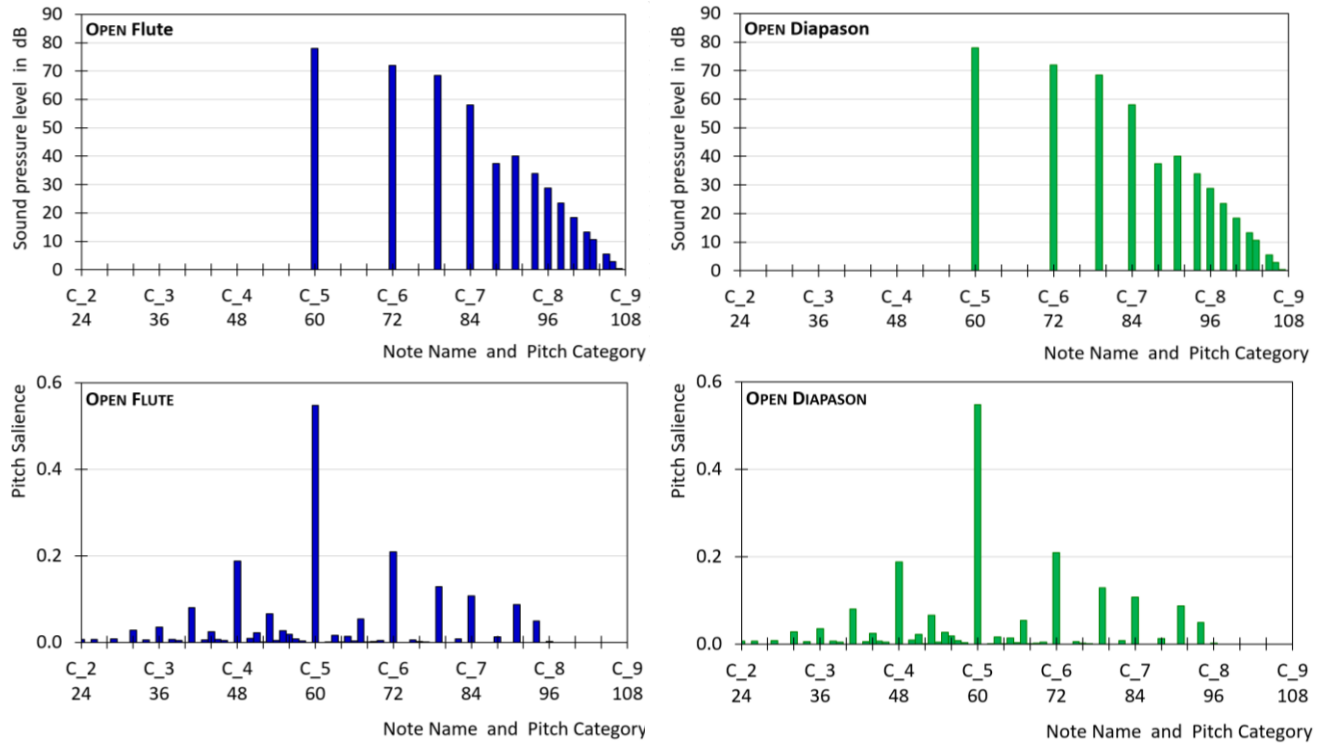


Figure 2. LTAS and pitch salience charts of an OPEN FLUTE (left) and an OPEN DIAPASON pipe (right) at C_5 .

I. NUMERICAL EXPERIMENT: WHICH TIMBRE PROVIDES MAXIMUM PITCH SALIENCE?

Maximizing the pitch salience $S(\Delta o = 0)$ of the CORNET for the nine combinations within the extended typical ranges for k_M and k_T results in values for the parameter F within the range $F = -11 \dots -10$, which is almost equal to the value of a typical OPEN FLUTE (Table 1). Exchanging the rank with OPEN DIAPASON pipes one obtains values for D in the range $D = -2 \dots 0$ and the average value $D = -1$ almost exactly matches the value in Table 1. In both cases, the CORNET achieves the maximum value for $S(\Delta o = 0)$ with “standard” ranks, marked as dotted lines in Fig. 1. For $k_M = 12$ dB/erb and $k_T = 1$ or $k_T = 3$ the values of $S(\Delta o = 0)$ for the CORNET with OPEN FLUTE pipes are larger than with OPEN DIAPASON pipes, in all other cases it is vice versa. Since the correct values of the three model parameters are unknown and will vary between different listeners, it is impossible to decide with this method which of the two ranks makes the CORNET “better” in the sense of maximum pitch salience $S(\Delta o = 0)$.

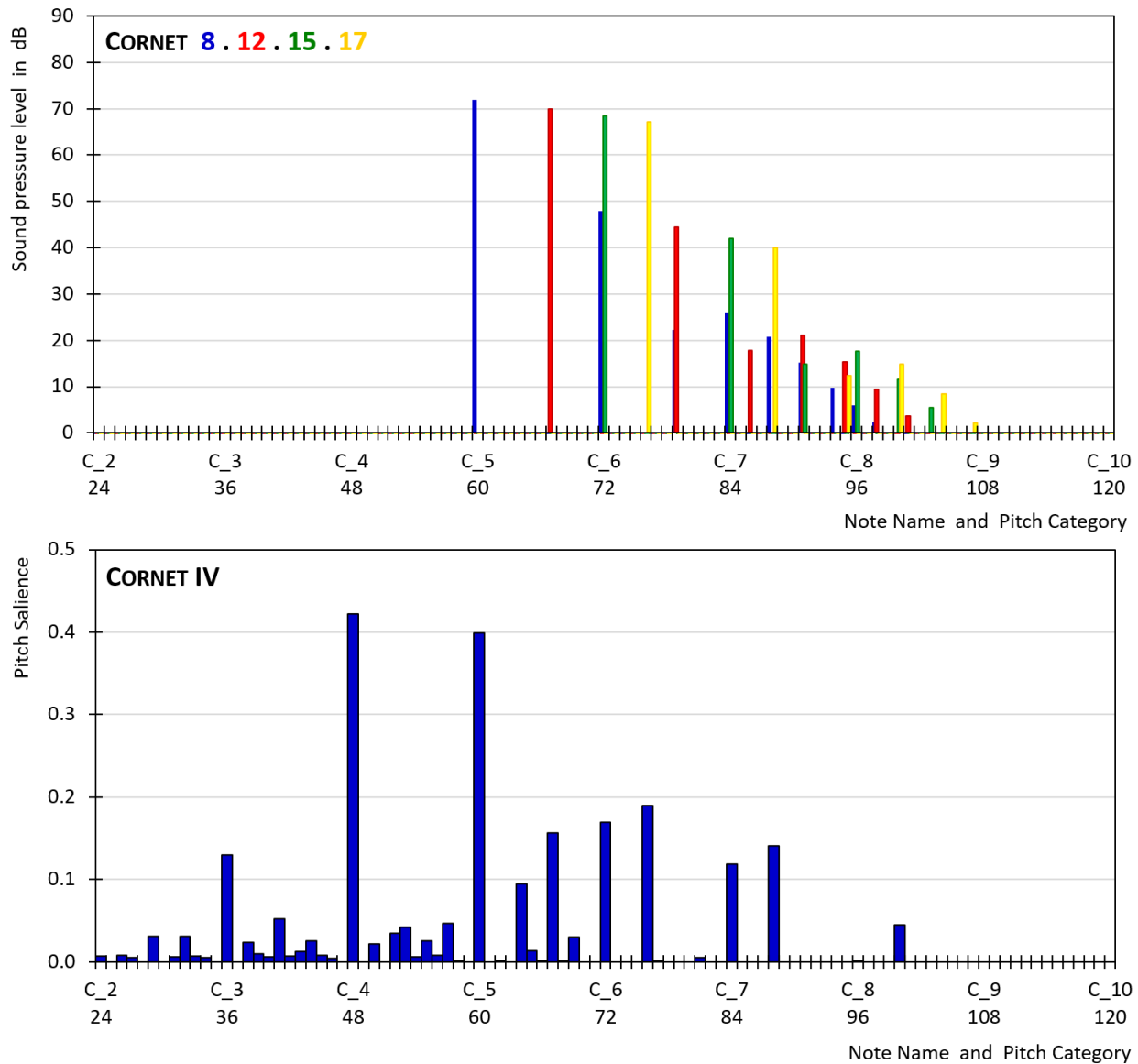


Figure 3a. LTAS (top) and pitch salience chart (bottom) for the CORNET at the note C₄.

The maximum pitch salience values $S(\Delta o = 0)$ of the ACUTA within the parameter field mentioned above are reached for $F = -3 \dots +5$ (OPEN FLUTE pipes) and $D = 0 \dots +6$ (OPEN DIAPASON pipes). However, such values for F are unrealistic, meaning that they do not correctly represent the timbre of FLUTE pipes anymore (in fact positive values tend towards OPEN DIAPASON pipes); in other words, there is no practical solution to achieve a maximal value $S(\Delta o = 0)$ with real OPEN FLUTE pipes. The solution for the OPEN DIAPASON pipes lies within a reasonable corridor, but for $D = +6$ with some string quality in the tone, e.g. like a GEIGEN DIAPASON (Fig. 1).

Fig. 3a shows the SPL for a four-rank CORNET according to Table 2 consisting of OPEN FLUTE pipes (parameters as in Table. 1 with $F = -10$); Fig. 3b depicts the SPL for the ACUTA IV according to Table 2 built with OPEN DIAPASON pipes (parameters as in Table 1 with $D = +4$). All diagrams refer to the situation in which maximum pitch salience at C₄ occurs, calculated for $k_M = 12$ dB/erb, $k_T = 3$ and $k_S = 0.5$. For both Mixtures the pitch salience at C₄ has increased compared to a single pipe at pitch C₅ (see Fig. 2). However, the pitch salience $S(\Delta o = 0)$ of Mixtures with octaves and fifths like the ACUTA could rise much more, if the OPEN DIAPASON ranks were exchanged by those of an OPEN FLUTE or, even better, by pure tones and, secondly, all partials $m > 1$ of the harmonic series were contained in the Mixture. This is partly realized in the CORNET ($m = 2 \dots 5$), but this principle is not in accordance with the practice of constructing other Mixtures. Thus, pitch salience is generally not sufficient to explain the pitch heights and SPL of the ranks in Mixtures.

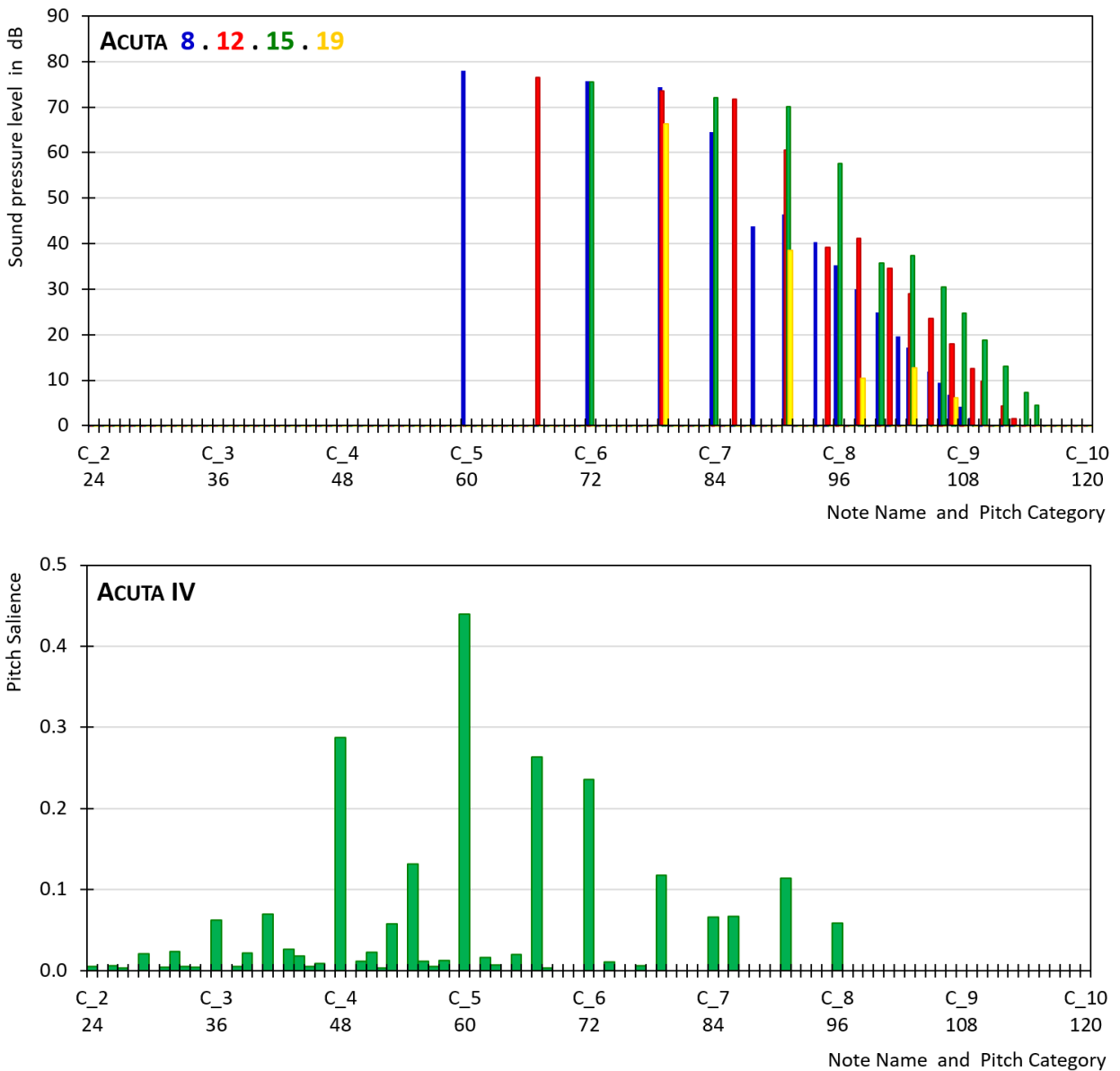


Figure 3b. LTAS (top) and pitch salience chart (bottom) for the ACUTA at the note C₄.

II. NUMERICAL EXPERIMENT: MAXIMIZING PITCH SALIENCE FOR EACH MIXTURE

Also this numerical experiment aims for maximum pitch salience at the fundamental pitch $S(\Delta o = 0)$. Therefore the SPL differences $\Delta L_{1,3}$, $\Delta L_{1,4}$ and $\Delta L_{1,5}$ (or $\Delta L_{1,6}$) are calculated the CORNET and for the ACUTA. Both Mixtures contain either only OPEN FLUTE or OPEN DIAPASON pipes for selected values for F and D .

In case of the ACUTA the algorithm pulls the SPL differences ΔL_3 and ΔL_4 of the OPEN DIAPASON towards large negative values, because this is the best solution to obtain maximum pitch salience $S(\Delta o = 0)$. As consequence, this four-rank Mixture does not make use of all its ranks anymore and no sensible comparison to the ACUTA with OPEN FLUTE pipes or the CORNET is possible. However, this clearly expresses that Mixtures are not at first place designed to generate the maximum pitch salience value $S(\Delta o = 0)$.

The refinements of the CORNET, however, yield reasonable values depicted in Fig. 4 and comprised in Table 3. The pitch salience $S(\Delta o = 0)$ is greater for the OPEN FLUTE than for the OPEN DIAPASON combination. Fig. 4 also implies that $S(\Delta o = 0)$ increases when the parameters F and D decrease meaning the timbre becomes more “flutey”. The values shown in red are the multiplicities M' of the tones with four pipes sounding

simultaneously. The values M' behave approximately inverse to the pitch salience and they correspond to the average number of individual tones recognized by a listener⁴. In these examples the multiplicities are $M' \approx 2.4$. Following the idea that the individual ranks within a Mixture should merge yielding the impression of one sound rather than a chord implies to minimize M' . However, this approach must also fail, because the value of M' for a single pure tone is always lower than that of a complex tone or several complex tones like in a Mixture.

Table 3. SPL for maximum pitch salience for given values for F and D in the CORNET.

CORNET containing OPEN FLUTE pipes							CORNET containing OPEN DIAPASON pipes						
F	$\Delta L_{1,2}$	$\Delta L_{1,3}$ in dB	$\Delta L_{1,4}$ in dB	$\Delta L_{1,5}$ in dB	S ($\Delta o = 0$)	M'	D	$\Delta L_{1,2}$	$\Delta L_{1,3}$ in dB	$\Delta L_{1,4}$ in dB	$\Delta L_{1,5}$ in dB	S ($\Delta o = 0$)	M'
							+9	0	+6.7	+4.5	+0.0	0.354	2.53
-4	0	+0.8	+0.0	+7.2	0.419	2.39	+6	0	+6.7	+4.3	+0.0	0.378	2.57
-7	0	+1.1	+0.0	+4.1	0.421	2.38	+3	0	+7.3	+3.5	+0.0	0.389	2.57
-10	0	+0.0	-0.3	-0.1	0.422	2.37	0	0	+7.0	+3.5	+0.0	0.393	2.54
-13	0	+0.0	-4.5	-3.6	0.419	2.38	-3	0	+0.8	-5.4	-8.3	0.396	2.52
-16	0	+0.0	-3.8	-3.7	0.434	2.30	-6	0	+0.0	-7.0	-12	0.399	2.50
-19	0	+0.0	-12	-9.6	0.447	2.24	-9	0	+0.0	-7.1	-14	0.403	2.48

Note: Values in **bold** were constant during the refinements. Fig. 4 visualizes the data in the columns S and M' .

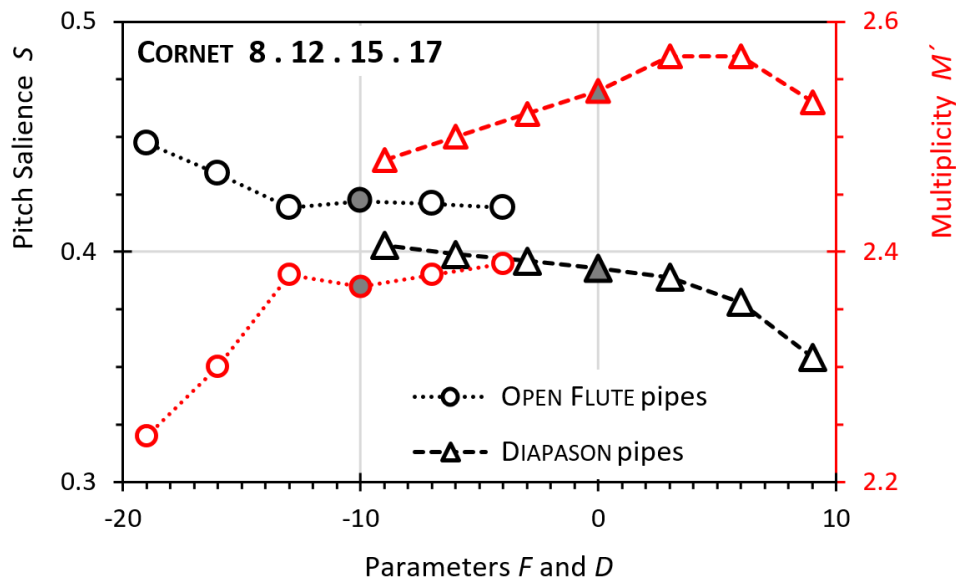


Figure 4. Pitch Salience and Multiplicity for two variants of the CORNET.

The conclusion from these two numerical experiments on pitch salience is unexpected. Firstly, Mixtures do enhance the pitch salience $S(\Delta o = 0)$ to some extent, because their ranks are tuned to be part of a common harmonic series. However, Mixtures do not aim to achieve maximum pitch salience $S(\Delta o = 0)$. This would require OPEN FLUTE instead of OPEN DIAPASON ranks and focusing on the low-pitched mutation ranks.

The second surprise is that Mixtures are not designed for minimal multiplicity, which seems to contradict the idea of the ranks blending with each other.

Contrary to these two statements, FLUTE Mixtures like the CORNET and its derived forms (SESQUIALTER etc.) seem to be exceptions, i.e. forming a different tonal class of Mixtures.

3. PITCH HEIGHTS AND CRITICAL BANDS

A. WHY TO INVESTIGATE THIS PARAMETER

Playing more organ pipes simultaneously increases the loudness of the tone. In medieval times the “Blockwerk” provided additional pipes tuned in octaves and fifths with the unison pitch and thus the melody became much louder than several pipes all at unison pitch¹. Moreover, high-pitched pipes require less space and wind supply compared with an array of plenty of unison pipes. The total loudness is given by Zwicker’s loudness approach⁶ and foots on the critical band concept and auditory masking⁶. To achieve the maximum loudness percept, Mixture ranks with different pitch should not fall into the same critical band. Therefore this chapter pursues the question, if the design rules for Mixtures agree with those for maximum loudness.

As already mentioned, the pitch heights of the ranks constituting a Mixture belong to a common harmonic series. Denoting its fundamental frequency as f_1 , the individual ranks within a Mixture will have fundamental frequencies which are integer multiples of f_1 , i.e. $f_m = m \cdot f_1$. Hence, the frequency difference of the ranks (referring to their fundamental pitch) cannot become smaller than $\Delta f = f_1$. This rule avoids generating acoustic roughness for all frequencies $f_1 \geq 125 \text{ Hz}$ ⁶, possibly already from $f_1 = 65 \text{ Hz}$. Consequently, Mixtures on the manual key compass $C_2 \dots C_7$ (eventually apart from the lowest notes) do not cause acoustic roughness.

B. RESULTS

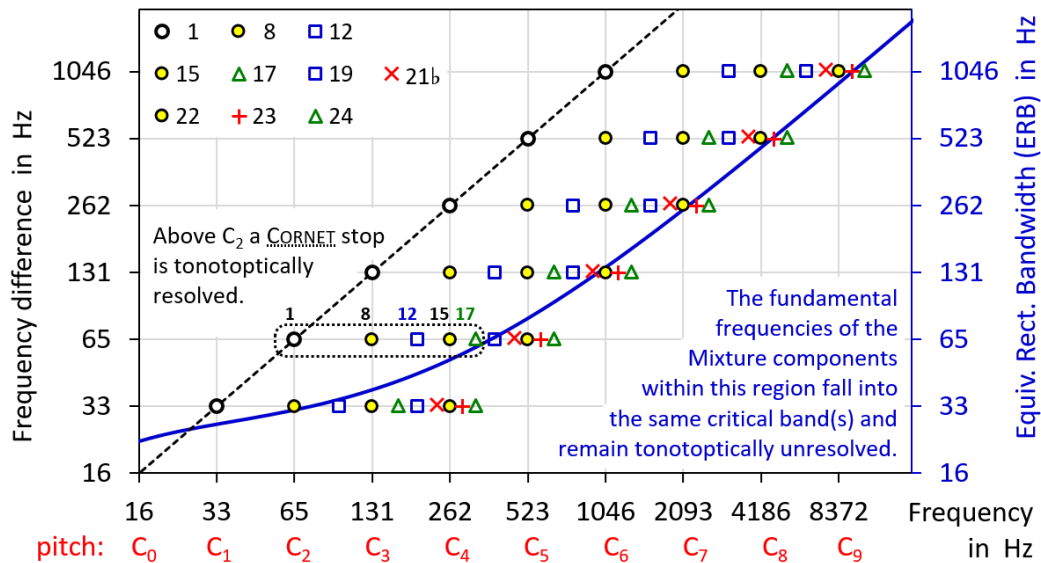


Figure 5. Mixtures of the CORNET type (pitch heights in diatonic numbers, 1 = unison) in relation to the ERB⁹.

For this investigation, the CORNET serves as a useful starting point, because this Mixture frequently begins at the fundamental and continues with the subsequent partials. For simplification, the sound spectra are reduced to pure tones. The frequency differences between the pitches of a Mixture determine the corresponding pitch distances measured in equivalent rectangular bandwidths (ERB). Fig. 5 depicts the situation for Mixtures without any gaps between the subsequent partials. Within the manual key compass a CORNET based on $8'$ does not generate any conflicts with ERB as long as the CORNET does not extend over the sixth partial. Latest when adding the ninth, the ERB will be too narrow. However, when omitting one of the high partials (e.g. using the 7th, 9th and 11th instead of the 7th, 8th and 9th) the ERB conflict is avoided, since the frequency differences between these partials are doubled. If a CORNET extends to the 9th partial, then the 8th (and usually the 6th, too) is missing.

In Mixtures (like the example of the ACUTA) it is common practice to omit pitches other than octaves and fifths, which avoids the problem of high-pitch neighbored partials. Even if high-pitched Mixtures contain rarely used harmonics (like the 11th and the 13th in Neo-Baroque Mixtures), they do not use neighboring partials. Not a single Mixture of the 36 for the manual keyboard described in Audsley’s book⁷ violates this rule, a pitch distance of 1.04 ERB is the minimum (Fig. 6a). This indicates that the roughness percept of the auditory system has determined how many neighbored partials work are tolerable within a Mixture.

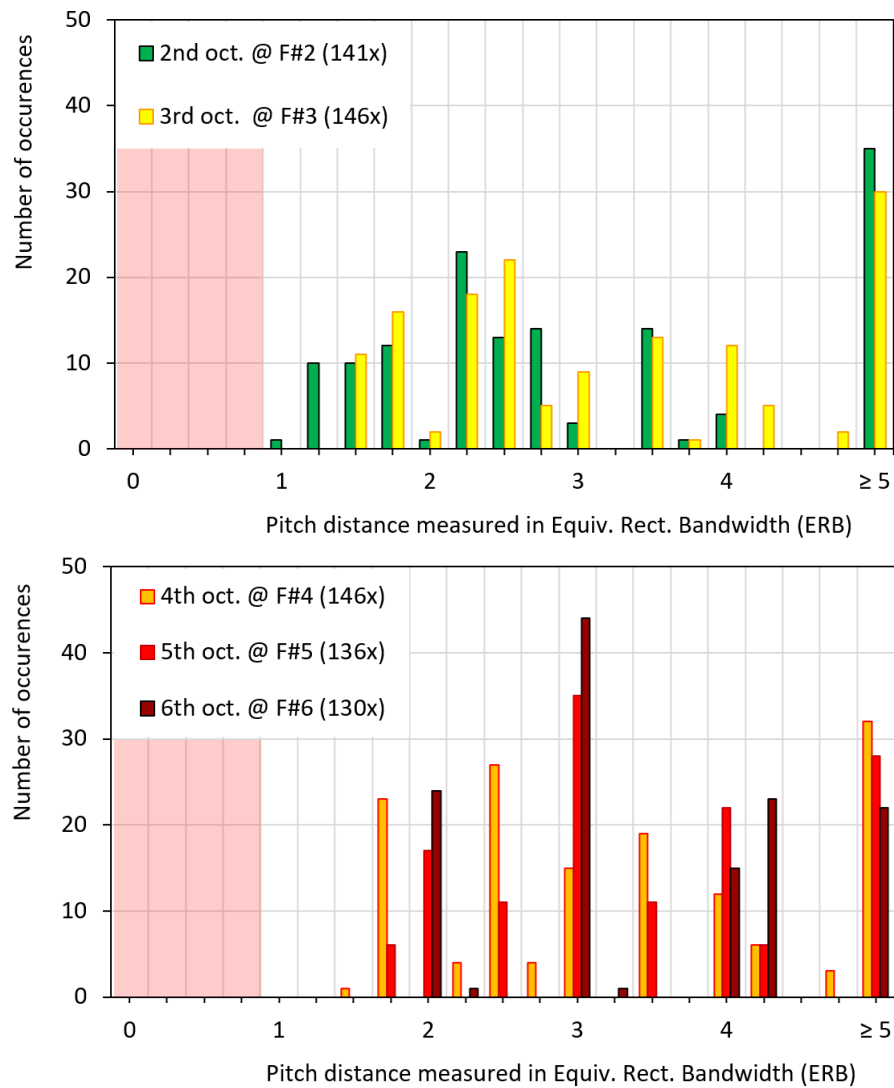


Figure 6a. Analysis of the pitch distances (measured in ERB) within 36 different Mixtures for the manual range.

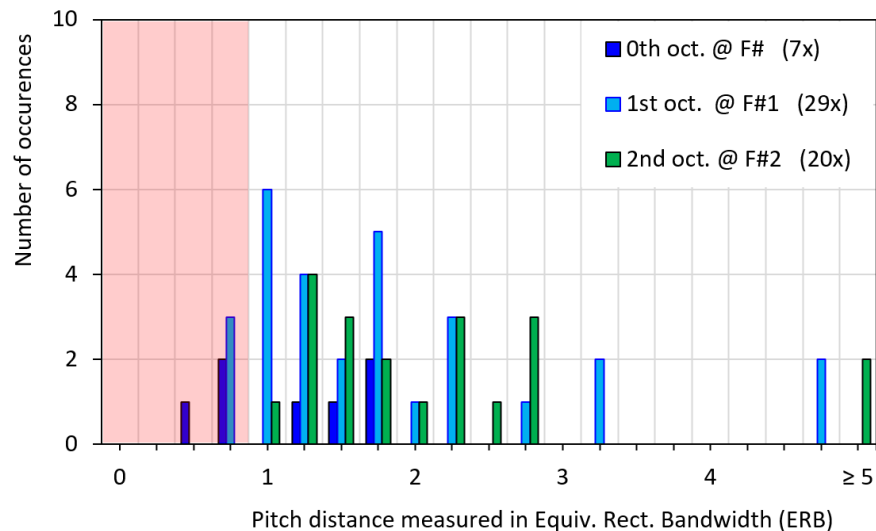


Figure 6b. Analysis of the pitch distances (measured in ERB) within six different Pedal Mixtures.

Even most of the pitch heights in Pedal Mixtures keep distances > 1 ERB (Fig. 6b). Note that the ERB classes in both diagrams of Fig. 6 possess equal widths given by the value on the abscissa $\pm 1/8$ ERB.

4. SHARPNESS OVER PITCH

A. WHY TO INVESTIGATE THIS PARAMETER

The tonal timbre “sharpness” is widely associated with the position of the spectral centroid c (measured in Hz). As Mixtures contain high pitched ranks they clearly contribute to the sharpness of the organ sound. Mixtures like the CORNET, in which the contributing ranks run from bottom to top evenly, show a different behavior of their sharpness over pitch than those, in which the ranks break back (Fig. 8, top). In principle, the scheme according to which the individual ranks within a Mixture break back could be adjusted for achieving a characteristic course of its sharpness over pitch. Thus, this chapter investigates the sharpness of different Mixtures searching for a common trend.

B. CALCULATION OF THE SHARPNESS FOR MIXTURES

The “unitless spectral centroid” c/f_1 , which involves a division by the fundamental frequency f_1 of that base pitch to which the Mixture refers to, is more convenient for this purpose as it does not depend on f_1 . If Mixtures consisted of pure sinusoidal tones (each with $c/f_1 = n$) each with identical SPL, the unitless spectral centroid (USC) of the Mixture were the average of the corresponding partial numbers n . For a five-rank CORNET (containing ranks at partial numbers $n = 1, \dots, 5$) this yielded $c/f_1 = 3.0$, the mean value of all n in this case. A precise calculation requires knowledge of the SPL of the Mixture – however, since this study is based on Mixture compositions in written form⁷, these data were not available. The tonal character of the ranks (which are not generating pure tones) in the Mixture can be taken into account by using the USC values of an accompanying investigation on LTAS of organ ranks²; representative numbers for three variants of the OPEN DIAPASON and the OPEN FLUTE are depicted in Fig. 7.

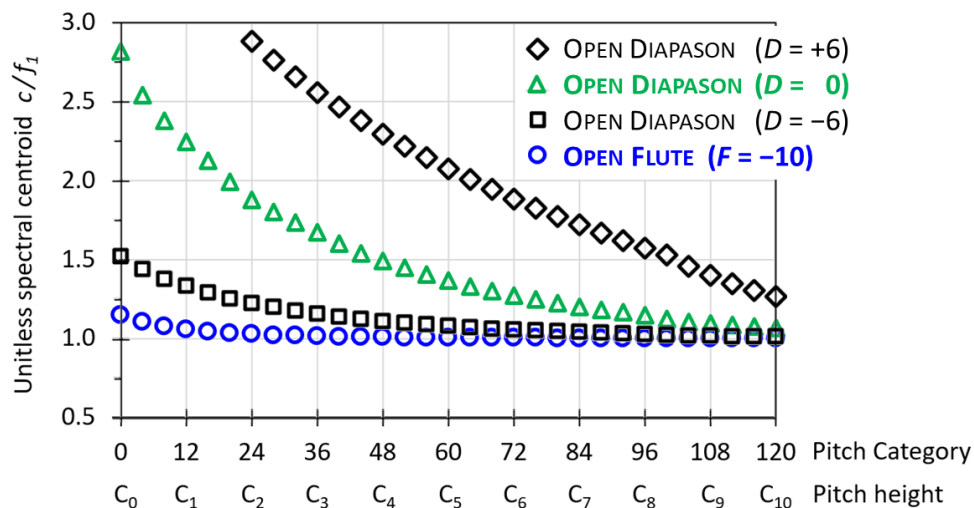


Figure 7. Correction factors for the unitless spectral centroid upon pitch of different ranks.

For the CORNET and derived compound stops (SEQUALTER, TERZIAN etc.), consisting of FLUTE ranks, which (normally) not break back within the manual key compass, the USC remains approximately constant over pitch. For “flutey” ($D = -6$) and standard OPEN DIAPASON ranks ($D = 0$) the USC values are below 1.5 in the high pitch range ($p \geq 48$), which is typically used for Mixtures on the manual key compass. OPEN DIAPASON ranks with a stringy tone quality (e.g. the GEIGEN DIAPASON) correspond to the top curve in Fig. 7 and add noticeable sharpness to a Mixture built from such ranks. The values in Fig. 7 may serve as corrections factors assuming equal SPL for all ranks in a Mixture. It also shows that the simplified approach to work with pure tones instead of complex tones for the individual ranks is a tolerable approximation of OPEN FLUTE and OPEN DIAPASON ranks, at least when the an OPEN DIAPASON is not too “stringy” in its upper pitch range.

C. RESULTS

Of all 36 Mixture compositions for the manual keyboard Audsley⁷ lists four Mixtures related to the CORNET: SESQUIALTER (ranks at partial no. $n = 3, 5$), TERTIAN ($n = 5, 6$), QUARTANE ($n = 3, 4$) plus the five-rank CORNET. In none of these four Mixtures the ranks break back and thus their USC is approximately constant upon pitch. However, the other 32 Mixtures contain ranks, which break back at least once, and the four-rank ACUTA mentioned earlier is one of them. The pitch-dependent USC of the ACUTA represents the 32 Mixtures well in that sense as its calculated values are close to their average. The values shown in Fig. 8 were obtained for equal SPL and pure tones; but, as described above, one could apply correction factors depicted in Fig. 7.

Contrary to the CORNET-type Mixtures with almost constant USC, the Mixtures in Fig. 8 loose sharpness from partial no. 8 at C_2 to about partial no. 3 at C_7 corresponding to $1\frac{1}{2}$ octaves, which is a typical value for the pitch distance how far the ranks break back within the key compass of five octaves. For comparison, Fig. 8 also contains the USC of three reed ranks studied in a related work². It seems that the 32 Mixtures use schemes according to which their ranks break back, which generate similar sharpness as the TRUMPET rank on the organ.

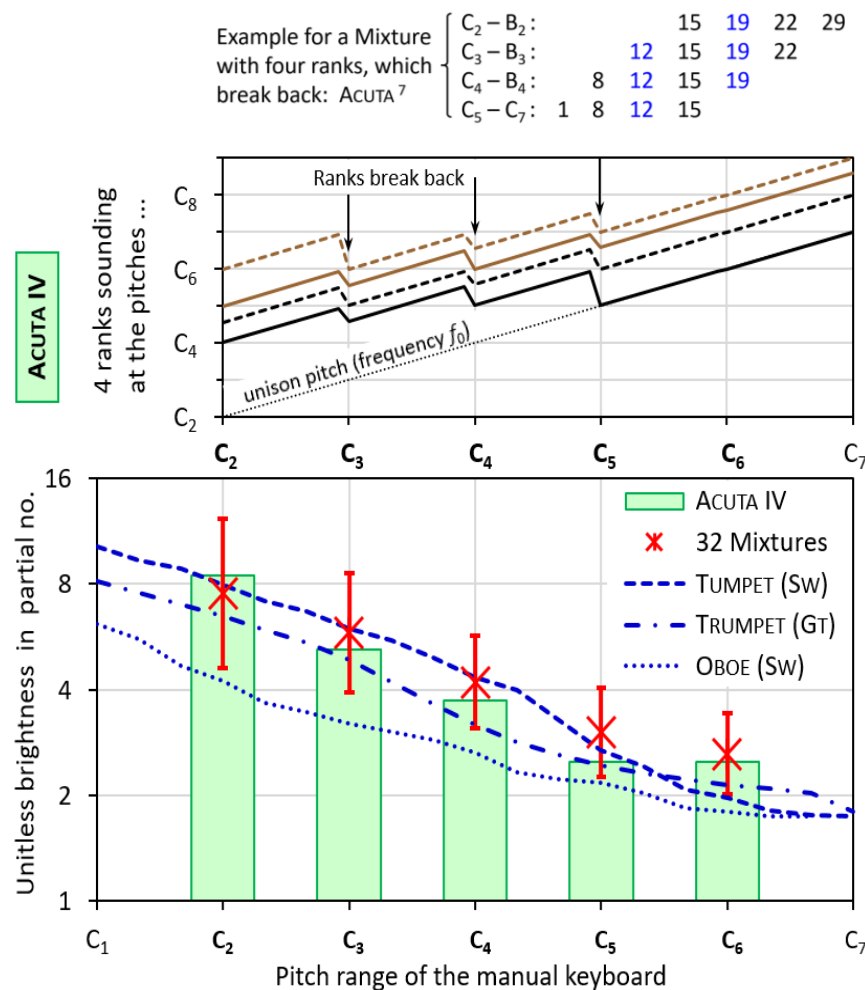


Figure 8. Unitless spectral centroid for the ACUTA IV as well as all 32 Mixtures compared to reed ranks.

For the sake of completeness, an example of a church organ built the John Compton Organ Co. (UK) shall illustrate a different approach for designing Mixtures. Its instrument for the East Kirk in Aberdeen, UK (built in 1936), contains twelve ranks and is highly unified. The Mixtures of this organ do not possess own ranks, instead they borrow their pitches from existing ranks (e.g. from the DULCIANA or the DIAPASON). Moreover, since none of the Mixtures breaks back, some of them run out of tones in the top octave, as there are no pipes higher than C_9 in this instrument⁸. Although all Mixture compositions are equal across the key compass (apart from the top octave), their USC is not constant. This is achieved by decreasing the loudness of the ranks with increasing pitch. This trick allowed Compton to avoid “breaks” in the Mixtures and to reduce the USC smoothly.

5. CONCLUSION

This study has investigated whether the underlying design principles of pipe organ Mixtures can be related to three selected psychoacoustic properties.

There is no short answer to the hypothesis that Mixtures are optimized to support the fundamental pitch. Due to the fact, that the pitch heights of the Mixture ranks are part of the harmonic series of the fundamental pitch, they do always enhance its virtual pitch and thus its pitch salience. However, the criterion to maximize the pitch salience at the fundamental is by itself insufficient to derive Mixture compositions. However, for the CORNET and its excerpts (SESQUIALTER, TERZIAN etc.) pitch salience at the fundamental seem to be relevant.

All 36 investigated Mixtures for the manual key compass and most of the six for the Pedal keyboard avoided that more than one pitch falls into the same ERB. Keeping a minimum pitch distance corresponding to one ERB yields to maximum loudness while simultaneously minimizing acoustic roughness.

The sharpness of most Mixtures falls into two categories: The CORNET and its excerpts does not contain ranks, which break back and thus have an approximately constant unitless spectral centroid over the key compass. However, the majority of Mixtures contains ranks, which break back – therefor their USC decreases from bass to treble. The course of the USC is similar to that of bright chorus reeds like the TRUMPET, the latter imitating the brass instrument of the same name. It thus seems plausible that the festive sound of the trumpet (to be precise: the sharpness of the constant sound after the attack) served as archetype and was involved in developing the sound character of the Mixture stops for the pipe organ.

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Furthermore, I like to thank Richard Parncutt for fruitful discussions on the concept of pitch salience at a very early stage of this work.

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