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INFLUENCE OF THE KEY PLAYED ON THE TIMBRE VARIATION OF RECORDERS

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ABSTRACT

Tone-to-tone variation of timbre is a characteristic feature of recorders of the Renaissance and Baroque era. Nowadays, original instruments are used as design models for recent flutes used in terms of historically informed performance (HIP). Typically, a variety of spectral types occurs at each individual instrument, which causes alterations of timbre throughout the scale played. Complicated fingering patterns contribute to this kind of variability. It is an individual feature of the particular instrument design because recorders are limited in intentional changes of timbre while playing a single tone. Timbre changes influence the overall appearance of musical motifs and scales. However, chromatic sequences manifest the full extent of variability. Based on the spectral types observed in previous studies, it is analysed whether a specific sound characteristic of specific keys (in the meaning of tonality) may occur during a performance. If a key is performed that on the circle of fifths shows a large distance to the basic key of the instrument, it is necessary to apply a large number of complicated cross-fingerings, which may cause increased variability. However, statistical evaluation of timbres shows that instruments are found that are stable in the statistical occurrence of spectral types, while others strongly vary in the occurrence of timbres throughout the twelve diatonic scales.

Keywords: *historical instruments, woodwinds, recorder, timbre, tone-to-tone variability.*

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1. THE ICONICITY OF TIMBRE

Aspects of timbre of music sounds can be described with a variety of psychoacoustic parameters. However, the human perceptual system spontaneously integrates data delivered via the sense organs to shape a total Gestalt of a sound. In this respect, the perceptual extraction of single parameters appears to be an additional conscious activity. It segregates components of a process that is originally holistic and thus configures an indivisible entity, whereby this holistic result of perception process cannot be quantified. In its nature as a percept, it is a model of the individual's surrounding (and inner) world. It cannot be derived by adding up or combining single psychophysical features. It holds much more importance to analyse the relation of an auditory Gestalt to other percepts of same or different modality and to memorised content. The perception and emotional effect of music tones is essentially determined by iconic aspects to which it refers, i.e., how what we hear "sounds like …" This leads to the need to apply the concept of iconicity to understand perception of sound and music. General concepts are missing and have been first developed by the author [1]. The iconicity of perceived content includes all associative aspects that are intuitively attributed to the stimuli. Sound thus communicates information on the nature of its source. Associative content is essential for the fit of specific sounds in the overall background and entire multisensory environment. Psychoacoustic parameters of sound contribute to the overall perceptual appearance of auditory elements, although the iconicity and semantic content determine the meaning of sound, which is most important to the listener. With the focus on music, this means that conscious and emotional uptake are indispensably determined by the iconic content of single tones, harmonies, and phrases. It is necessary to consider that the timbre variation due to spectral changes is modulated by the influence of pitch. The concept of timbre applied here considers two components of timbre, a *spectral* and a *pitch-dependent* contribution ([2], Fig. 1). It can be observed that the audibility of spectral differences declines with increasing pitch. This is one reason why it is increasingly difficult to audibly discriminate the various wind instruments from each other with increasing pitch. The present contribution is based on associative content of timbre, i.e., the similarity of instrumental sounds to other sound sources and respective instruments. It is beneficial to develop methods which allow assessment of timbre on the base of the iconic content of sound. Reference to colour scales facilitates hue and brightness as equivalents to timbre as the "colour" of tones. Furthermore, similarity of spectral properties generated by various instruments is a pathway to address associative features and possibilities of perceptual attribution of tones.

2. INHERENT TONE-TO-TONE VARIATION OF REORDER TONES

It is a challenge to play a historic recorder in an artistic manner because temporal and spectral tone parameters strongly vary throughout the total tone range. Adjusting those parameters that the player can influence is thus specific to nearly every tone. Timbre variations given by the instrument enrich musical expression, although they are only one component of tone variability, besides loudness, pitch, directivity, tone attack, sensitivity to articulation, sensitivity to air stream fluctuations, and others. Loudness is small with lower tones, and subsequently (but not monotonously) increases towards the highest register. Some high tones require closing the ending of the resonator tube, the bell by means of the knee or upper leg. Fig. 1 shows the recorded data of a Baroque recorder. Due to the use of non-calibrated equipment, the sound pressure scale is displayed relative to the magnitude of the weakest (=lowest) tone of the scale. The magnitude increases around 10 times from the lowest five tones to the highest tone that can be played (C_7). The timbre variation of the instrument is included in the spectra. Nevertheless, a comparison of the distribution of partial tones is hindered by the variation of fundamental frequencies. Normalisation of pitch will improve comparability. Air stream velocity is used by the flautists to adjust pitch and modify the temporal behaviour in terms of crescendo, decrescendo or vibrato. Within a small range, it can also influence the timbre. In fact, musicians need to search for and develop compromises of pitch, timbre, and loudness.

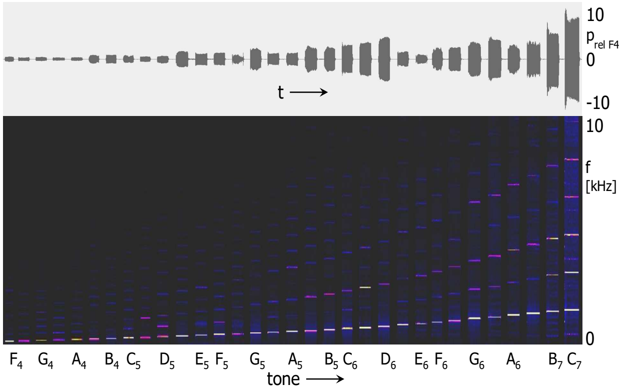

Figure 1. Recorded sound pressure of a Baroque F-alto recorder after Bressan, A_4 = 415 Hz, ebony. Chromatic series from F_4 to C_7, displayed in the time and frequency domain.

Intentional modifications of recorder timbres by the player are quite limited. Resonances of the vocal tract and the air stream itself have some influence. Timbre can be modified via size and shape of the mouth resonator [3], whereas the phase of coupling between instrument and vocal tract is the crucial parameter [4]. Training enables optimum adaption of both resonator systems, which are commonly described by input and transfer impedances. An optimisation of these resonators improves the efficiency of input energy provided by the player's air stream. Furthermore, the impedance tuning makes the tone generation less sensitive to disturbances within the windway, which may be caused by condensation water of breath humidity. A common and traditional method of intentional modification of timbre is the facilitation of alternative fingerings, which enable fitting enharmonic tones to just temperament, or achieving an equally tempered scale. Such methods have already been mentioned in the contemporary literature from Renaissance to Romanticism [5]. Alternative fingerings have also been recommended by versed players and teachers of transverse flutes, such as Anton Berhard Fürstenau [6]. Hence, the question on how specific fingering techniques influence the appearance and distribution of timbres throughout musical scales and themes is on the table since several centuries. It is here proposed to approach this topic by spectral classification and statistic evaluation of recorder timbres.

3. TIMBRE CHARACTERISTICS OF HISTORIC RECORDERS

Nowadays, the perception of timbre is gaining increasing scientific attention [7]. By contrast, sound and timbre were not in the focus of music theory until the end of the 19th century. This applies to the sensation of sound as well as physical considerations. Today, psychoacoustic studies aim to evaluate auditory perception. In the mid-18th century, Johann Mattheson complained that books about music included nearly nothing about sound ("Klang") and its physiology [8, Drittes Haupt-Stück. Vom Klange an sich selbst, und von der musicalischen Natur-Lehre. §1, p. 9]. However, his concept of sound is far reaching and thus includes the physical side. This approach differs from language use in modern German: Today, "Klang" refers to perception, and "Schall" means the physical field. In English, the term "sound" includes both sides of acoustics. For such reasons, there is no literature about timbre and its variations from the times when recorders emerged as one of the main woodwind instruments. Notes for recorders and transverse flutes were usually limited to the supposed dull sound generated by means of fork fingerings compared to tones that can be played with normal fingering, as exemplified in Fig. 2.

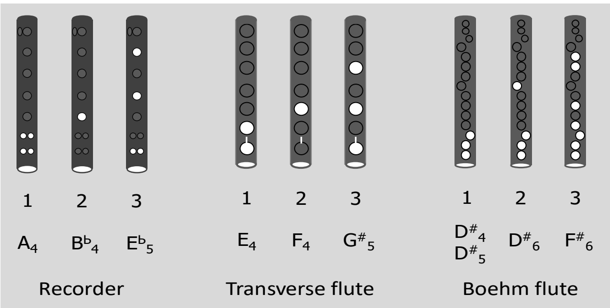

Figure 2. Examples of hole patterns used for flute intonation, showing the acoustic effect of finger application, not the finger patterns themselves.
1: simple fingering
2: fork/cross fingering
3: double fork fingering

In this paper, fork (or cross) fingering is seen as a matter of the acoustic effect, but not focused on the playing techniques. Each fingering pattern with open holes surrounded by closed holes is seen as a fork pattern, whichever fingers are used for it. Hans-Martin Linde states that the timbre change caused by fork fingering is more distinct with the Baroque flauto traverso that with the recorder [9, p. 34]. Timbre became a topic of discussion during the 19th century, closely connected to the development of the Boehm flute and the advancing shift away from inverse conical transverse flutes of the "old system" of fingering. With respect to the variation of timbre, Fürstenau, however, praises the benefit of fork fingering. For him, this provides changes from bright to dull timbres which are essential for expression of emotions [6]. Overall, alternation between normal and fork fingerings is a typical measure to gain a rich differentiation of timbre during the Baroque and Classic eras [5]. Hans-Peter Schmitz states that the different timbre caused by fork fingerings has been assessed as an advantage, because notes with accidental are audibly marked and may thus be clearly distinguished [10, p.13]. However, the prevalent opinion is that tones that need forked fingering sound weak and partly veiled. Moreover, the flautist and acoustician Jens Holger Rindel notes that spectra of those tones appear less clean [11]. Intentional modification of timbre by the player is limited with recorders and historical transverse flutes. The timbre variation from tone to tone is thus a characteristic *feature* of these instruments, which can further be enhanced by alternative fingerings. In contrast to a variety of wind instruments such as oboe and bassoon, flutes of the frequently used gamut (Boehm flute in C_4, transverse flute in D_4, alto recorder in F_4) do not show pronounced formants at fixed frequencies. Presumably, formants cannot establish with high pitch and a small number of harmonics. However, this fact underlines the timbre variation. It holds specific interest to explore the extent to which this variation influences the auditory appearance of specific musical themes and keys. Recorders in the Renaissance and Baroque design exhibit the spectral types shown in the upper part of Fig. 3. In the literature, chalumeau-like spectra are described as typical patterns. Thomas Lerch uses the term *duodecimal* tones. This type is also found with gedackt organ pipes and the low register of clarinets. At recorders it has been shown that the direction of air flow caused by the air stream centred towards the labium may be responsible for the weak 2nd partial tone [12]. By contrast, with modern and historic flutes *octavial* sounds with distinct second harmonic catch the listener's ear, which in principle do not occur with recorders [13]. The second partial tone allows for a smooth transition to the second octave, whereas recorders need a special thumbhole to enable overblowing.

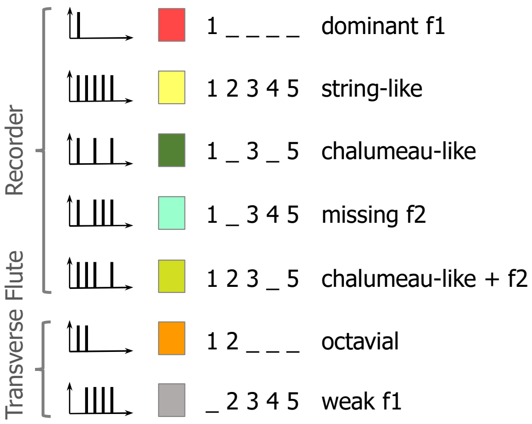

Figure 3. Characteristic patterns of harmonic partial tones 1 to 5 for recorders and transverse flutes.

The second partial tone of transverse flutes can be adjusted by the flautist's lips [12]. All spectra that have been found with recorders can also occur with transverse flutes. Spectra of flutes usually show a distinct fundamental tone f1. When playing the modern Boehm flute at low tones, it is also possible to intentionally weaken the fundamental and thus enhance the expressivity of sound. Each pattern is modified at various tones by additional harmonics towards a more string-like timbre, as indicated here by fading of the specific colour. Below, the alto recorders as shown in Fig. 4 in Renaissance and Late Baroque designs will be analysed. All tones of the gamut have been played in chromatic order, i.e., F_4-D_6 with Renaissance, F_4-C_7 with Baroque recorders. Spectra have been classified according to [2] and [14] and labelled by colours according to Fig. 3. Due to the COVID-19 pandemic, recordings had to be done at home with equipment owned by the musician. Zoom H2 handy recorder equipment was used with sample rate 44.1 kHz. Signal processing in Wave-file format was performed with REAPER (cockos), final processing by WavePad software (NCH). Recording was done in 1m distance in front of the instrument, at height 1m. The aim of this project is to demonstrate the principle of timbre variations on period woodwind instruments, which can be achieved without perfect standardisation of measurement equipment and environment. The type of wood is documented to identify the instrument. It may have some influence on timbre but is not seen as a decisive factor for the variation from tone to tone.

Figure 4. Alto recorders investigated: Six instruments built according to historical Renaissance and Baroque designs.

The classification of these instruments and the resulting colour scale has been previously described [2, Fig. 5]. As an overview, descriptive statistics of the pattern of partial tones across the gamut are here shown in Fig. 5.

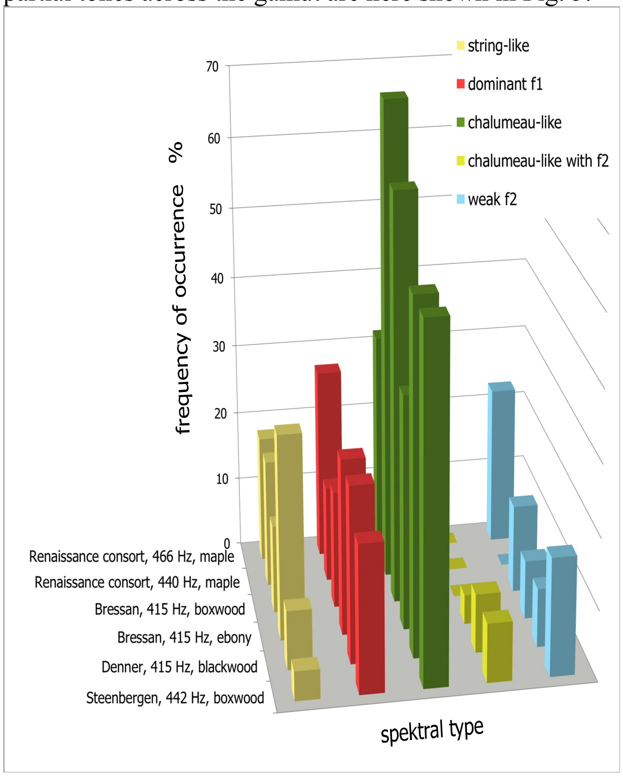

Figure 5. Spectral statistics of the recorders investigated for the chromatic scale within the lower two octaves. See black line in Fig. 8.

Naturally, the statistics disregards the sequence of timbres. The statistics verify the dominance of the chalumeau-like timbre. This is a typical pattern of partial tones to which the term *duodecimal* applies, in contrast to the *octavial* behaviour found with transverse flutes. From his studies, he concludes that recorders used in the music of the 18th century nearly exclusively show duodecimal characteristics [13, p. 162]. Nevertheless, spectra with dominant fundamental and those with string-like characteristics have also frequently been found with the instruments investigated here.

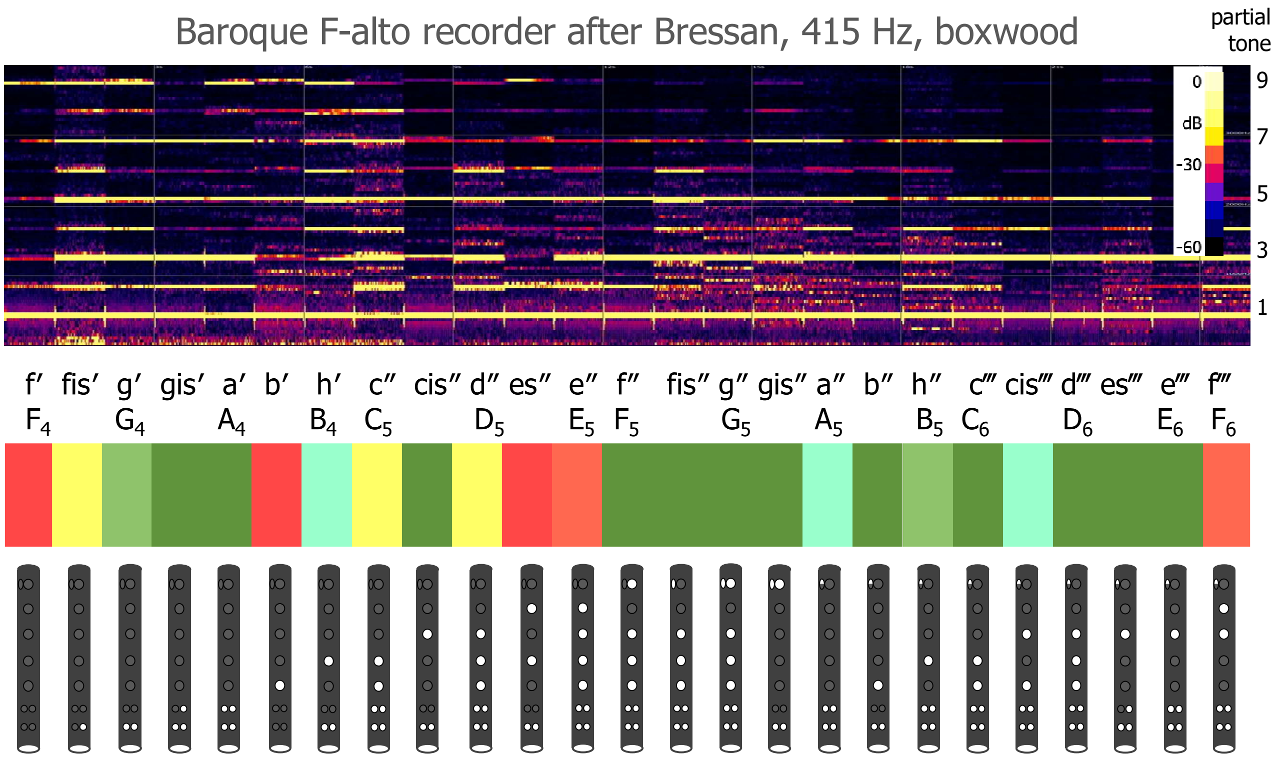

Figure 6. Spectral analysis normalized to fundamental frequency, classification, and hole patterns of a Baroque F-alto recorder after Bressan, boxwood, 415 Hz.

As an example of the effect of hole patterns on the occurrence of partial tones and thus excited spectral types, Fig. 6 shows the result of analysis of one recorder. Even with normal fingering, spectral types vary significantly. A fixed relation between cross fingering and spectral type does not exist. This finding would need more detailed analysis, which is not the topic of this study. Here, change of spectral types from tone to tone is obvious. At the instrument used, this especially applies in the lower register.

4. TIMBRE AND MUSICAL THEME

The inherit variation of timbre is driven by the specific geometry of the instrument, which determines the acoustic properties of the resonator. For this reason, replicas of the various originals also show individual characteristics across the chromatic scale. When playing a musical sequence, e.g., a theme, patterns of timbre occur that are characteristic for the specific instrument [2]. The same occurs when a sequence is transposed into a different key. As described above, various cues can be found in literature regarding the influence of fork fingering on the timbre of historical transverse flutes. If this applied to the recorders studied here, the timbre patterns would increasingly differ from the basic key of the instrument (with all finger holes closed) when distant keys are reached around the circle of fifth. Fig. 7 demonstrates the effect of transpositions on an F-alto recorder of Late Baroque design. Again, the theme by

Georg Philipp Telemann is played, which was used in [2] for comparison of various recorders. In the recorder edition of the composition, the original key is G major. However, the fundamental key of the instrument used here is F major. The transpositions shown here consider three keys around the fundamental key and three keys with maximum distance throughout the circle of fifth. In comparison to the written key G major, all transpositions have been done downwards. For the keys C and B flat major close to the instrument's fundamental key F major, a high frequency of occurrence of string-like spectra and those with dominant f1 (yellow and red) is observed. However, the distant keys F sharp major, B major and E major express a dominance of chalumeau-like sounds (dark green) as well as variants with additional f2 or f4 (light green or light blue). All other spectral types of recorders according to Fig. 3 can also be found.

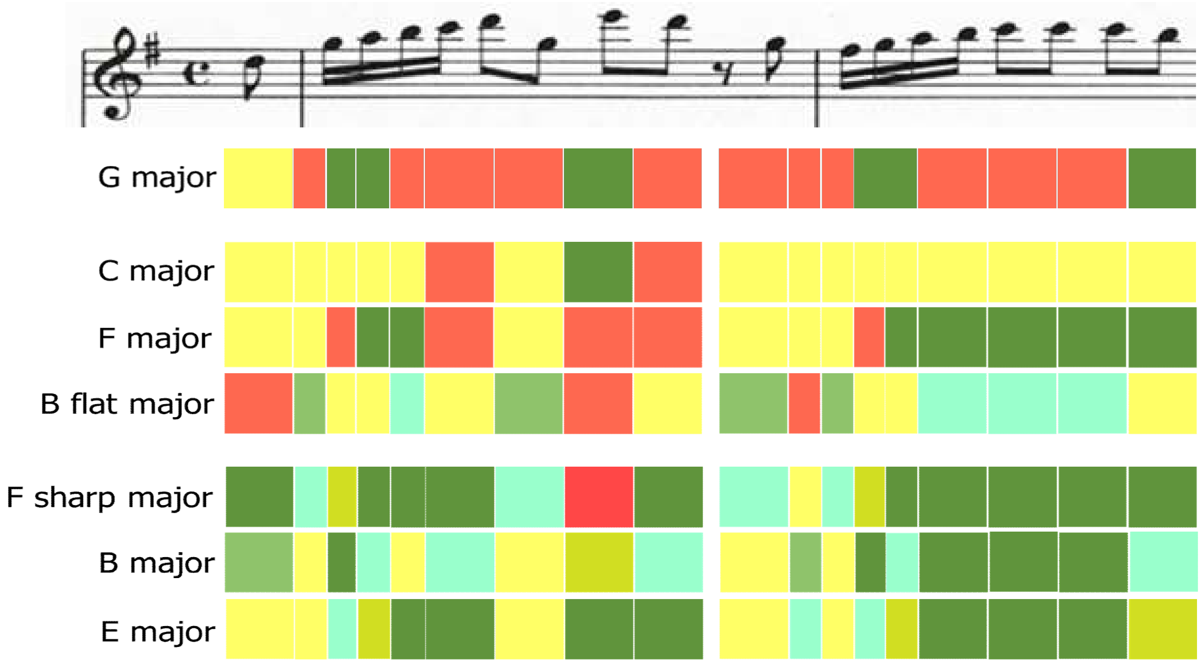

Figure 7. Example of spectral variation when playing a melody. Top: original key G major. Below: keys close and distant to the fundamental key of the instrument. Baroque F-alto recorder after Bressan, 415 Hz, ebony. Theme of Sonata 6, Affettuoso, from 6 Sonatas for 2 Flutes by Georg Philipp Telemann (TWV 40:106).

Overall, a shift to chalumeau-like (1_3_5) and related spectral types (1_345 or 123_5) can be noted. Recorders of Late Baroque design are configured for a system of "Baroque fingering" that more or less requires fork fingering in all keys. However, around the fundamental key, the number of such tones is much smaller than for distant tonalities. The frequency of occurrence of the spectral types found with recorders is shown in Fig. 8 for all diatonic keys of the circle of fifth. The black line demonstrates the chromatic behaviour of the respective instruments, with data taken from Fig. 5. Data of all diatonic scales are included in the diagrams. Given that the descriptive statistics includes fifteen tones for the lower two octaves of each key, the graphs often overlap. If the variation is small, not all curves can be seen.

5. TIMBRE CHARACTERISTICS AND KEY

In order to verify the predication of dependence of the overall timbre of a played key caused by the number and kind of fork fingerings, the spectral types are analysed for each diatonic scale. Again, the instrument used is the recorder built after Bressan (415 Hz, ebony). Given that the spectral types do not appear in a systematic series, the relation between the key and overall timbre can only be analysed in a statistical manner.

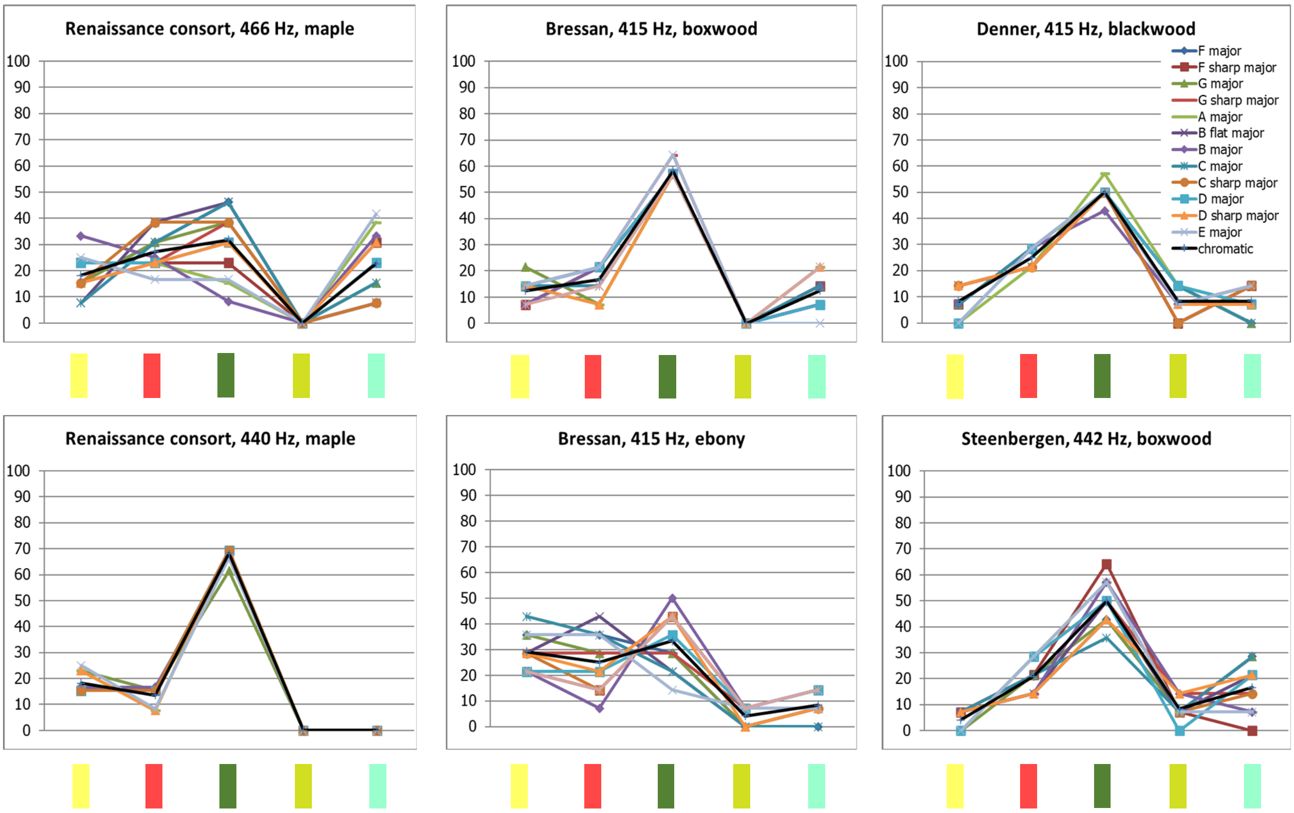

Figure 8. Statistics of spectral types of the recorders investigated for all major scales within the lower two octaves. The colours at the abscissa indicate the spectral types as defined in Fig. 3. Statistics of all tones added as black line.

Three of the six flutes show a distinct influence of the key played on the descriptive statistics of timbre. However, this influence is small with the other instruments. The deviation is especially small for the Renaissance consort flute tuned at 440 Hz, given that this instrument has a chalumeau-like behaviour throughout a major part of its chromatic scale (from B_4 to B flat $_5$). The statistics exhibit a strong influence of the key played in case of one of the flutes built according to Renaissance designs (Fig. 8 top left). It is also strong with the ebony Bressan flute used in Fig. 7 for demonstrating the timbre variation caused by transposition of a melody (Fig. 8 bottom middle). The distinct influence of key on the timbre statistics coincides with the observation when transposing the melody. For this instrument, it especially relates to the occurrence of string- and chalumeau-like tones as well as those with a dominant fundamental. The physical root cause of the different behaviour of the recorders investigated could not be evaluated here. This would require detailed acoustic measurements with the respective instruments. However, besides following historical geometries, instrument makers apply individual fine tuning to their replicas. This fact is suspected as a reason for the different sensitivities of timbre statistics to changes of musical key. It thus is plausible that even instruments that follow a similar design – like the two flutes after Bressan – can exhibit different timbre variabilities and stabilities towards alterations of key, as shown in Fig. 8.

6. CONCLUSIONS

The analysis confirms the distinct tone-to-tone variation of timbre found with recorders in Renaissance and

Baroque designs. The six instruments studied show a prevalence of chalumeau-like spectra, which exhibit the harmonic partial tone f1, f3, and f5. String-like spectra with evenly harmonics and those with dominant f1 also occur. At some tones, the chalumeau-like behaviour occurs with additional f2 or f4.

The characteristic variation of timbre causes musical sequences and themes to sound different. This depends on the design, configured by the instrument makers of both the historical original and the rebuilt instrument. It also provokes a dependence of timbre distribution on the musical key. As a major contributor, the timbre of key is caused by the kind and occurrence of fork (cross) fingering. However, for tone generation, the acoustic effect of finger patterns is decisive, but not the choice of specific fingers and hands. It should be noted that with recorders of Baroque design there is no key that does not require any fork fingering.

Although a systematic comparison of timbres for normal versus fork fingering could not be done here, data did not show a systematic correlation between spectral type and hole patterns applied. The overall statistics of timbres for the chromatic sequence across the tone range depend on the flute design. Therefore, the timbre variation across all keys can be quite different. Among the recorders analysed, two cases have been observed:

1. Three instruments show a low statistic variation. This is equivalent to a high stability of timbre distribution across all diatonic scales.

2. The other three recorders show a high variation of the timbre statistics across the keys. This means that the occurrence of spectral types varies for all diatonic keys.

7. ACKNOWLEDGEMENTS

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