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Subjective and objective evaluation of the tone-to-tone timbre variability of historical flute designs.

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Abstract
During the seventeenth and eighteenth century, the variability of timbre of music instruments in terms of a 'tone colour' was essential to enhance the emotional involvement of the audience, the naturalness of expression and the language-likeness of instrumental sounds. An expression of multi-sensory content by 'painting with music' was popular. Timbre is the essential base of the colourfulness of music. Given that flutes of that era show a more simple design than the modern flute, specific fingering patterns are thus needed for the full chromatic scale, which causes a characteristic variation of timbres from tone to tone. For the first time, this study compares the natural timbre variability of recorder and Baroque transverse flute (traverso) with the modern Boehm flute. Possibilities of subjective comparison are discussed. Perceived timbre is seen from a phenomenological point of view. It combines a pitch-dependent portion with effects caused by the distribution of partial tones and formants. For the subjective approach, the pitch dependent portion of timbre perception is removed. This enables subjective evaluation of the influence of partial tones on timbre perception. Objective acoustic analysis of spectra clarifies the associative content with a view to similarities with other instruments. Colour scales are used for a brief overview on the tone-to-tone variability of an instrument. Such colour scales prove to be beneficial to qualitatively document the associative content and its variability in the sense of tone colour. The results indicate that the total sound of each instrument is based on a variety of spectral properties/timbres rather than unique properties for all tones. Surprisingly, this also applies to the modern flute that has been developed for similarity of perceived tone quality throughout the scale. Each flute type shows variable references to sounds of other instruments. Timbre variation is not an error state, but it essentially contributes to the music aesthetics of the Renaissance and Baroque era.

Keywords: flute, recorder, timbre, tone-to-tone variability, colour scale, HIP

1 Introduction

Throughout the last 200 years, improvements of woodwind instruments have been based on acoustic understanding and systematic calculations. These efforts have improved intonation for equally-tempered scale as well as the tonal and dynamic ranges of instruments. Moreover, the aim has been to achieve a substantial uniformity of timbre throughout the whole tone range, as well as improving the possibilities of players' creative influence on the music parameters.
However, in contrast to the development of increasingly powerful instruments, the popularity of historic instruments has grown in approximately the last 50 years. Numerous concerts have been performed, and a nearly endless number of recordings have been published. One element of this trend is the rediscovery of historical ways of performance, phrasing and articulation in terms of 'historically-informed performance' (HIP). Another essential contributor is the reproduction of historical sounds by means of period instruments. One argument for the usage or reconstruction of such historic instruments is the awareness of the aesthetic correlations between the composer's intent, the listener's taste and the tone qualities, which depend on the

instrumental capabilities. In other words, it is understood that the historic timbre and dynamics is an intrinsic part of any contemporary composition. It is neither simply a result of the limited skills of the instrument makers, nor caused by a lack of knowledge on the acoustics of tone generation and the perception of sound.
For this reason, it is meaningful to compare the timbre of historic instruments and appropriate replica with modern types, whereby historical flutes hold particular interest. The flutes family divides into two groups with different excitation principles: the transverse flute and the recorder. Recorders of the Renaissance and Baroque eras show different timbre due to major geometric differences [1]. The design of the transverse flute changed twice during three centuries: from roughly cylindric to conical (tapered towards the foot) and back to a cylindric bore [2]. These design changes caused essential modifications of tone properties [3, 4]. In comparison with the modern Boehm flute, it is supposed that the timbre behaviour of historical transverse flutes and recorders is characterised by a higher variability from tone to tone.
Prior to analysing this feature, it would be beneficial to consider the aesthetic preconditions of the respective eras. Due to space restrictions, this shall be a topic of a separate paper.

2 Timbre and other qualia of instrumental sound

Since the beginning of research on music perception, the question on the nature of timbre has always been a core theme. During recent years, this discussion has gained intense actuality [5]. However, the description of timbre is a complicated task. In contrast to pitch, it is neither a single feature that can precisely be described by a single quantity – such as the frequency in Hz – nor does it find its unambiguous place in a graphical representation, like a specific height of a note within staves. If we imagine a sound event that is clearly distinguished from the acoustic background as an entity, it has a specific Gestalt in our perception [6]. However, due to the qualia problem of perception, we are unable to precisely communicate this 'sound object' to other subjects. Timbre is not caught by a single quantity or simple terms, because it is an essential portion of the whole Gestalt. Many quantities as spectral properties relevant for timbre have already been evaluated, such as spectral centroid, attack time, brightness, and others [see e.g. 7]. An evaluation of auditory descriptors of a Baroque transverse flute and various Boehm flutes is provided online by the University of Vienna [8].
A first approach for understanding the relation between physical spectra and perceived timbre of sound has been developed by Hermann von Helmholtz, who stated that the instrumental timbre depends on the number and magnitude of the partial tones [9, p. 113f]. This finding remains a good base to search for differences in the steady-state appearance of tones, especially in case of instruments with a small number of partials and high fundamental. It is also a good starting point for estimating the associative content of sound and similarities between instrumental timbres. In case of flutes – which typically feature a relatively small number of partials – it is beneficial to focus on the approach by Helmholtz by first comparing the steady-state spectra themselves. The proportion of the magnitude of single partials towards each other is then crucial for the perceived timbre, because the onset and release phase of the signal are intentionally ignored. It is self-evident that a focus on the partials of each tone is beneficial in the case when various tones of an instrument show different spectra. Therefore, seeking uniform timbre behaviour throughout the whole tonal range of an instrument would require spectra for all tones with a comparable relation between the main harmonics. Similarity thus means the same distribution of magnitudes of partials relative to the given fundamental frequency.
Beside the relations among the partial tones, the absolute frequency of the fundamental influences the perception of timbre. Pitch is not an attribute of sound that can be heard separately, whereas timbre includes the main perceivable aspects of the auditory Gestalt of a sound. Pitch is simply a descriptor that can be evaluated from an auditory perception. Pitch and timbre are thus not simply orthogonal dimensions of a perceived sound. In order to understand the influence of the partial tones on the perceived timbre itself, it is meaningful to standardise all tones of an instrument to one frequency, whereby the spectral differences are clearly perceivable. However, the timbre of a tone shifted in frequency is different from the real timbre composed from partial tone distribution and real fundamental frequency. At flute instruments with tone ranges equal or above c'/C4 – like those investigated here – pitch is always related to a measurable

fundamental frequency. Perception of a pure residual pitch does not occur because tones with completely suppressed fundamental do not exist.
Investigations of a variety of instruments have shown that formant-like parts of spectra can determine the perception of timbre. The formant-driven concept of instrumental timbre has been developed by Karl Erich Schumann [10]. Schumann's formant theory implies that fixed formants induce the timbre that is typical for a specific instrument and its auditory interactions with other instruments. Formants thus represent the musical timbre of many instruments and of the human voice. The spectral analysis of flutes presented herein, however, has proven that in this case formants do not play a major role for the perception of timbre. It is thus appropriate to focus on Helmholtz's perspective. With view to a pragmatic approach on perception of timbre of musical tones, it is evident that

- Tones of similar pitch change timbre with their spectral content, i.e. the pattern of partial tones.
- Tones of similar spectral content change timbre with pitch, represented by the fundamental frequency.

Even if a pure sinusoidal tone is shifted in frequency, listeners will report that high pitch will sound "somewhat" different than low pitch of the tone. For a demonstration of the tone-to-tone variability of instrumental timbres, it is thus beneficial to separate both influencing factors from each other: the spectral content and pitch. If pitch of a variety of instrumental tones is standardised to a single value, the spectral influence on timbre variability becomes clearly perceivable, although it includes a modification of the real timbre. Figure 1 visualises the effect in case of instruments with uniform spectrum such as a simple electronic keyboard compared to historic and modern flutes. This concept is here applied for subjective and analytic comparison of complete tone scales of flutes.

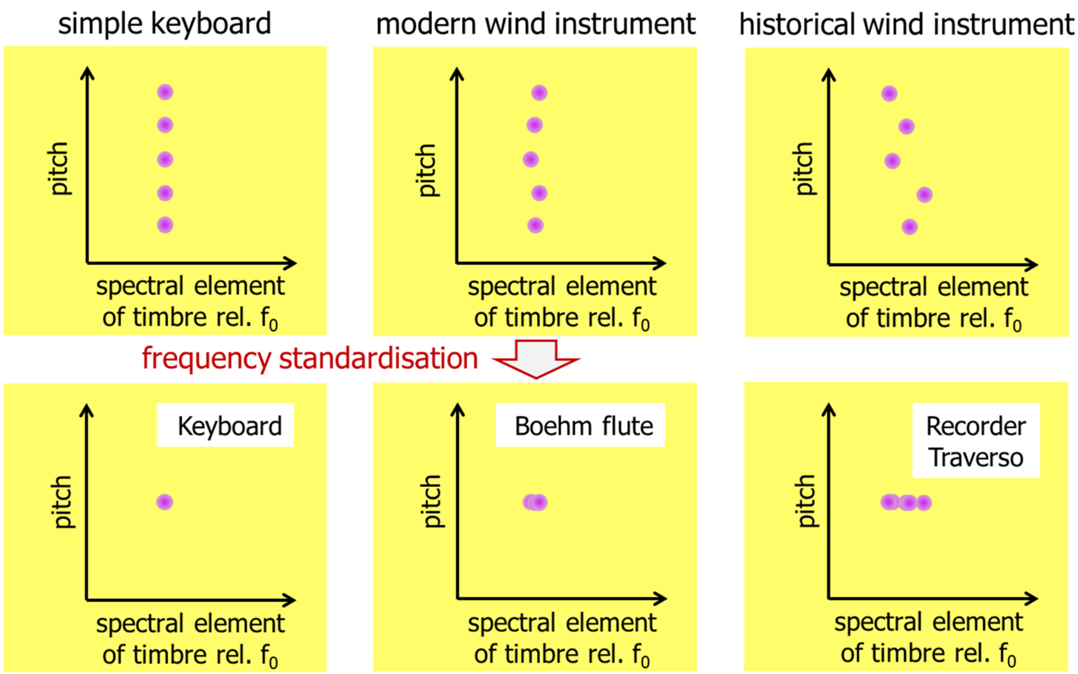

Figure 1: Effect of frequency standardisation for subjective comparison of spectral contributions to timbre.

The subjective method is suitable for demonstrating and comparing timbre variations of woodwind instruments without major influence of formants. The analysis of steady-state spectra includes estimating spectral similarities with other instruments and helps to establish colour scales for visualisation of timbre variability.

3 Instruments used

Both subjective and objective methods have been proven with various instruments. Due to the fact that original builds were not available, replica were analysed which are used for soloistic demands of HIP. Naturally, these designs imply some adaptation on recent requirements of playing techniques, such as double holes. Examples discussed herein are (Figure 2):

- Baroque F-recorder after Pierre Jaillard Bressan (1663-1731), boxwood, a'/A4=415Hz
- Baroque traverso after Carlo Palanca (1688-1783), blackwood, a'/A4=440Hz
- Boehm flute, solid silver, ring keys, solid silver mouthpiece, with golden lip plate, a'/A4=440Hz

Additionally, flute and recorder stops of a simple electronic keyboard (a'/A4=440Hz) have been used as a reference for a complete lack of timbre variability.

Figure 2: Instruments for which results of timbre variability are herein discussed.

4 Subjective comparisons of timbre

Various examples of flute tones can be found online. A comparison of single tones for transverse flutes is documented in [11]. Sound examples and a set of descriptors can be picked here [8]. Both documentations, however, do not include recorder sounds.
In this study, the pitch-dependent part of timbre is separated from the portion that depends on the spectral pattern itself. This approach allows an uncomplicated overview of the overall variability of timbres of various instruments. It is proposed to shift all tones to the same fundamental frequency by means of a time-domain operation such as stretching or squeezing in order to avoid signal distortion. Thus, a *timbre/spectral profile* of all chromatic tones is achieved. In this first approach, standard pitch (415, 440, or 466 Hz) is used as the reference. Sound recording was conducted in front of the player at a distance of 1m, and a height of 1m. The complicated directivity of sound radiation influences the spectral properties of sound and the perceived timbre. Furthermore, directivity differs from tone to tone due to the variation of fingering patterns. However, a definite direction of recording provides a situation similar to the fixed position of the listener of music performances.
It should again be emphasised that the result comprises tones with modified pitch, except the single tone, which already shows the reference pitch. Nonetheless, the timbre profile makes it much easier to gain an idea of the spectral changes within the chromatic scale. Specifically, this applies if the subjective impression is compared with the objective analysis, as described below. It is reasonable that the proposed method may cause some confusion if the instrumental sound is dominated by fixed formants. An additional analysis has clarified that formants do not play a major role for timbre of the given instruments.

Besides timbre changes, the auditory variability of tones played with period instruments extends to further parameters:

– The loudness that can be achieved with one tone differs due to the limited dynamic range of these instruments. This also influences the possibility to perform crescendo and decrescendo.
– The temporal response of the instrument differs with different tones. It thus influences articulation/attack phase, the tone release phase, and the potential of vibrato, which is performed by means of either airstream or finger movement.
– The potential precision of intonation varies from tone to tone.

These influences have been eliminated. Players were instructed to avoid vibrato and loudness changes during playing. A “natural” instrumental tone was required without application of particular playing techniques. Tone cut-out was used to eliminate onset and decay, which were substituted by standard envelope curves to avoid any clicks. All signals have been normalised in magnitude. The COVID-19 pandemic impeded the use of one identical equipment and recording room for all players. Recordings were thus conducted with stereo recording equipment used by the musician, such as Zoom H2 handy recorder or comparable devices. Signal processing in Wave-file format was performed using REAPER (cockos), final processing by WavePad software (NCH). The measurement location in relation to the instrument was standardised as mentioned above. 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. In case a detailed comparison of instruments with small differences is intended, a more precise proceeding would be required. An essential advantage of the proposed timbre profile is given by the possibility to simply arrange test setups for specific questions. Tones can be sorted for a chromatic scale, or other series. Specific selections can be made, such as arrangements of tones achieved with simple fingering compared with those which require cross-fingering. As result of the procedure, a set of standardised signals for the full chromatic scale is available for all instruments.

5 Objective comparison of spectral properties

The adjustment of all tone recordings to the standard pitch of the respective instrument and an equal magnitude enables a simple visual comparison of spectra along the whole scale. Given that the timbre of most tones of the investigated flutes is defined by a relative small number of partial tones, this provides an elementary overview of timbre variations. In a further step, the timbre variation is described by comparison of partial tone patterns of different instruments, like clarinets, string instruments and organ pipes. This provides a first glance at the associative potential of timbre, which refers to sounds of other instruments, and which varies from tone to tone in case of historical instruments. Finally, the spectra are sorted with a view to similarities with other instruments. This provides the possibility to use colour codes for a summary of timbre variations. In figure 3, the pitch range of the Baroque recorder built after Bressan is analysed for two octaves from f′ - f‴ (F4 – F6). Alternative fingering for dis″ is used, noted as es″. The strong variation of timbres from tone to tone can be understood with a view to the various types of spectra that occur. In case of this Late Baroque recorder, four principle types can be distinguished. Some tones show a dominant fundamental frequency f1 (Figure 4, top left). The fundamental f1 is present at each tone of the recorder, but usually supported by a variety of harmonics that clearly differentiate the flute timbre from a pure sinusoidal tone. The colour code is used for colour scaling of timbre classes as described below. Some tones show a wide spectrum with seven or more strong partials (Figure 4, bottom left). This behaviour generates a smooth, string-like timbre. As an example, the spectrum of a violin tone is characterised by a high number of harmonics with slightly decreasing magnitude towards the higher partials. String-like timbres of organ pipes are intended to simulate such instruments, like the orchestra-viola [12, p. 252]. Typical examples here are observed at fis’/F#4 and c’’/C5. The most typical behaviour of a Baroque recorder with its distinct conical bore is characterised by protruding uneven-numbered harmonics f1, f3, f5 and f7 (Figure 4, top right). While f3 is the second partial that occurs, the behaviour has been named “duodecimal” [13]. This spectral feature is well known from organ pipes with a closed tube, named ”gedackt” or “gedeckt” (German for “covered”) [14, p. 252]. This is also typical for the lowest register of the clarinet. Helmholtz already knew this behaviour and its effect on the perceived timbre [9, p. 180-1].

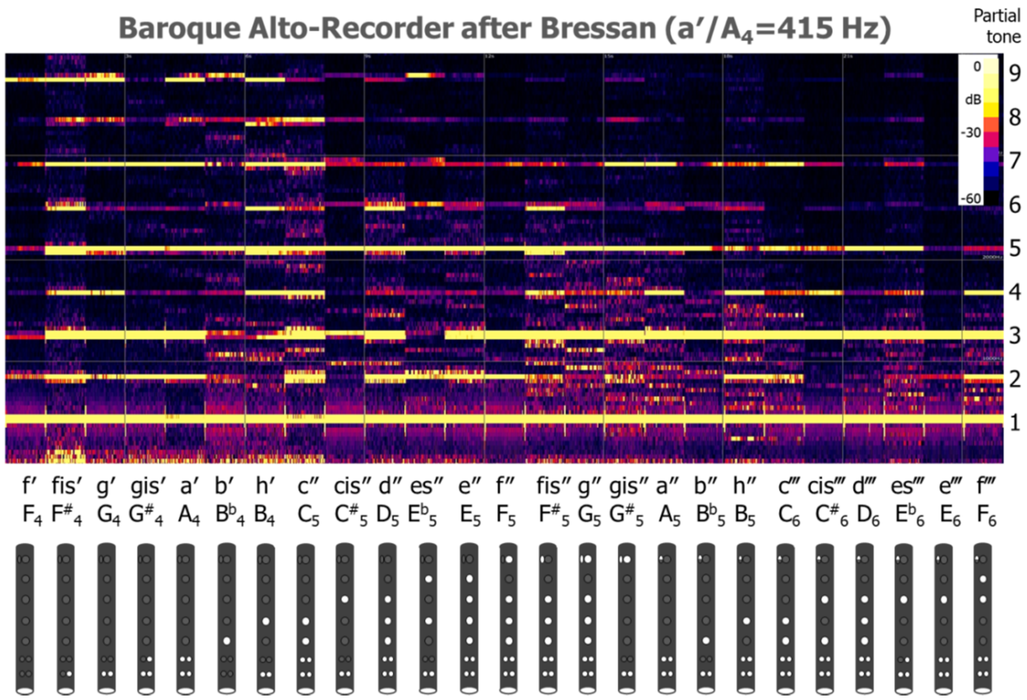

Figure 3: Spectral profile of an F-alto recorder of the Late Baroque period. Spectra normalised and shifted to 415Hz. Hole pattern added to distinguish between simple- and cross-fingering.

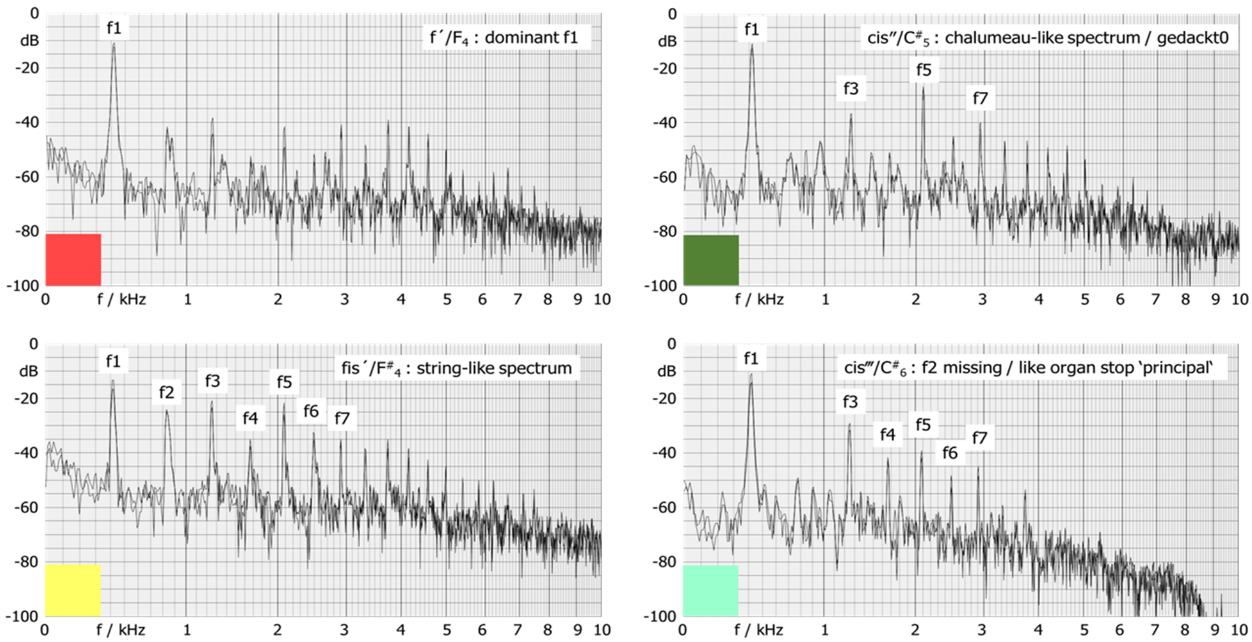

Figure 4: Typical spectra of an F-alto recorder of the Late Baroque period.
The audio signal is normalised and shifted to 415Hz.

This spectral behaviour is herein named “chalumeau-like” with reference to the so-called woodwind instrument that was quite popular during the Baroque era. Its design is similar to the recorder, but makes use of a single reed like the clarinet instead of a windway with labium. The chalumeau-like behaviour typically occurs at many tones of recorders. It is the spectrum most frequently found at the Baroque instrument investigated here. This finding confirms that it is a determining feature of Baroque recorders. At some tones, the spectrum shows a homogenous group of partials, but without a distinct f2 (Figure 4, bottom right). This type is known from the open organ pipes of the principal stop [14, p. 252]. The principal is the most bright register of the organ. It was the only register of the organ used until the Renaissance era. The principal stop manifests the typical sound usually associated with the acoustic organ.

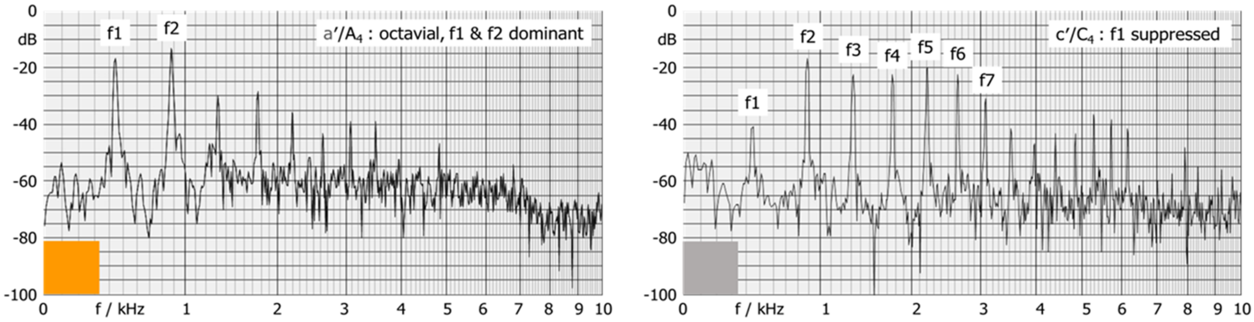

Figure 5: Typical spectra of transverse flutes such as Baroque traverso and Boehm flute.
The audio signal is normalised and shifted to 440Hz.

A special behaviour of transverse flutes is the strong contribution of the second partial tone f2. This is mainly observed in the lower octave. At some tones, f2 can exceed the magnitude of f1 (Figure 5 left). Such “octavial” behaviour is very typical for transverse flutes. It usually does not occur at recorders [13]. By contrast, the chalumeau-like duodecimal behaviour observed at recorders is an exception in spectra of transverse flutes. Nonetheless, it can occur at single tones. In case of the observed Palanca-flute, this was found in the spectrum at g’’/G5 and gis’’/G#5. Pure chalumeau-like spectra have not been identified there. Two exceptions occurred at dis’’/D#5 and d’’/D5 with slightly pronunciation of the first odd partials. Such type of spectrum mixed from string- and chalumeau-like contributions is marked with a light green colour (spectrum not shown here). Furthermore, inharmonic partials occur in some cases, but these tones may have a minor influence on timbre due to their low magnitudes. With respect to the dominant f2 at many tones of the transverse flute, and the overall typical octavial characteristics – in contrast to frequent duodecimal spectra of recorders – it can be concluded that these are spectral features which clearly distinguish transverse flutes from recorders. These spectral characteristics audibly distinguish the steady-state timbre of both types of flutes, although this does not apply to each single tone. Furthermore, it explains why transverse flutes do not need an octave hole/flap, because enhancement of f2 by means of the embouchure allows smooth switching to the upper octave. This opportunity does not exist with the typical chalumeau-like spectra of a recorder. At the Boehm-flutes investigated, string-like and octavial spectra occur most frequently. A broad spectrum of harmonics can be generated at specific tones of the Boehm flutes. Such spectrum is often further characterised by an extenuated f1, as found in the lower register (Figure 5 right).

6 Visualisation of timbre variation as colour scales

In order to provide a brief overview of the timbre variation of each flute, the application of a colour code has been examined for this study. Each aforementioned type of spectrum is characterised by a specific colour. In the past, various trials have been made to attribute colours to tone pitch, with a focus on either the auditory perception or physical properties of sound and light [15]. Many people, however, intuitively connect colours to timbres, as a result of fundamental studies on synaesthetic perception [16, 17]. However, in this study the colours are intentionally chosen and thus do not refer to a subjective synaesthetic perception. The specific colour refers to the types of physical spectra as described above, by means of the following attributions:

The most characteristic spectra found at the investigated recorders are shown in the upper line, including the frequent chalumeau-like behaviour. Additional variants found at transverse and Boehm flutes are included in the lower line. As stated above, the octavial type is typical for transverse flutes. The colour scales for the instruments exemplified here are depicted in figure 6. Mixed spectra are indicated by increased brightness of the colour code. As an example, a string-like spectrum with a slight duodecimal contribution is indicated by a light green colour.

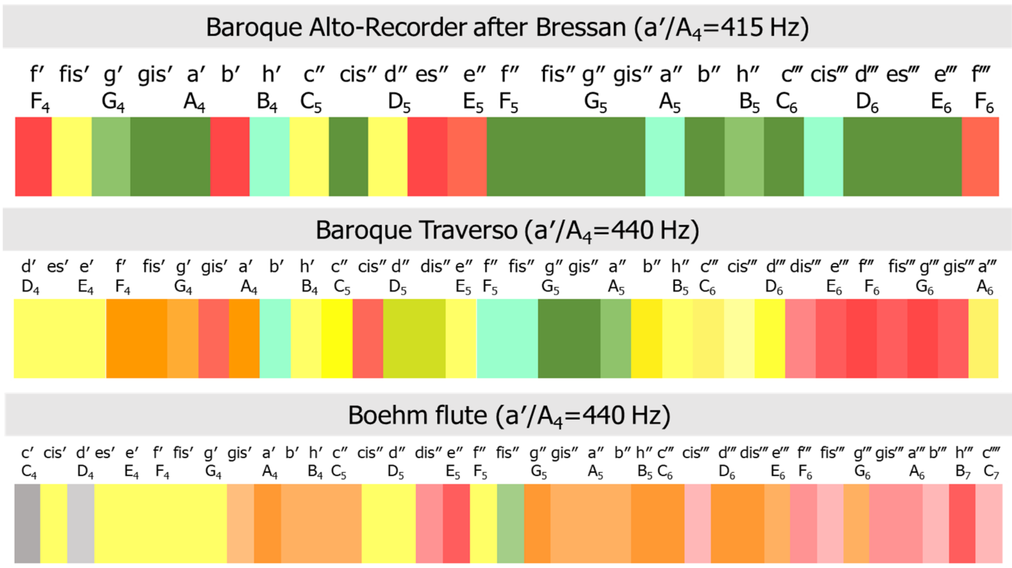

Figure 6: Colour scales related to the timbre profiles of the described Baroque recorder and the traverso compared to the Boehm flute as described above.

The chalumeau-like spectrum occurs at recorders of both Renaissance and Baroque era. Enhanced studies verify that this sound feature is the most distinct of Baroque recorders [18]. Spectra with dominant f1, string-like and principal-like behaviour are also found, but scattered over the whole tone scale. The colour scales thus illustrate the strong variability of timbres from tone to tone, literally the *colourfulness* of flute sounds.
The majority of tones of the investigated traverso shows octavial or string-like properties. Dominance of f1 is typical for the third octave. Chalumeau-like spectra are seldom but evident at g”-a” (G5-A5). At d”-dis” (D5-D#5), such spectra show an additional f2. Some tones have spectra similar to principal organ pipes. Therefore, when compared with the results of recorders, the tone-to-tone variation of timbres is not significantly reduced at the transverse flute. On the other hand, it is not more pronounced. This finding is contrary to Linde’s statement that the timbre variability is more pronounced for the Baroque transverse flute rather than a recorder [19, p. 34].
However, the Boehm flute spectra appear to be more equalised but by no means homogeneous between all tones, as aspired by Boehm [20]. String-like and octavial tones as well as those with protruding f1 characterise the timbre profile overall. Few exceptions are the chalumeau-like characteristics, only at fis”/F#5, and spectra with extenuated f1. As mentioned above, a comparison of different instrument designs to the full extend would need a high number of instruments, players, and operating modes such as variation of the embouchure.
This first approach was intended to derive new possibilities for describing the timbre variability of woodwind instruments. Colour scales are beneficial to gain an overall impression of the timbre behaviour of

such instruments throughout the tone scale. They help to compare the spectral variations and the main tendency of all flutes. Furthermore, they refer to comparable timbres of other instruments. In case of the appearance of distinct types of spectra, the attribution to colours is easy, although the attribution of the various mixed types of spectra is a challenge. It is still uncertain where the borderline has to be set for clear differentiations, such as transition of a spectrum with dominance of f1 to a spectrum of further harmonics, or the limits at which a chalumeau-like spectrum morphs to a string-like type. The aim of colour selection was to provide an intuitive overview of the highly complicated pattern of timbre variations of flutes, and explore the possibilities and limits of such approach. It is still a challenge to establish colour scales that are strictly consistent for both the subjective (auditory) *and* the objective (physical/acoustical) appearance of spectral variations. Nonetheless, in combination with the subjective impression of the standardised signals, the colour scales displayed in figure 6 provide a strong impression of the relevance of timbre variations and help to draw conclusions regarding the principal differences in sounds of various instrumental designs.

7 Conclusions

The standardisation of recorded tones regarding similar magnitude and pitch is helpful to gain understanding of the variability of timbres from tone to tone. This is important due to the fact that the associative/iconic content of timbre cannot be quantified. Furthermore, the method is beneficial for subjective evaluations of specific questions, such as concerning the effect of cross-fingerings or features of instrument design. A colour scale is useful to gain a quick visual overview. It is based on the distribution of partial tones, thus providing a reference to comparable instrumental sounds. This colour scale may need some more systematic elaboration on the assignment of specific colours to specific spectra features. It is essential to provide objective criteria for classification of the spectra. A further method development shall include appropriate auditory descriptors, like the spectral centroid. The brightness of the colours used can then be aligned with analysis results of spectral brightness. Continuative investigation need to include more instruments, dynamic variations and various players.
All flutes investigated in this study show a specific variability of timbres throughout the scale. This applies to the early designs from Renaissance and Baroque, but surprisingly also to the modern Boehm flute. It is essential to understand the formation of sound perception of each instrument based on its variety of spectral properties and thus timbres, not just based on a selection of single spectra that are generalised. A simplified description of the timbre of historical flute designs that tends to embrace all tones with few words is not beneficial considering the high variability of timbres. By means of the colour scale, it is possible to perceive the multiplicity of timbres upon one glance. It avoids rash jumping to a generalisation on "how the instrument sounds". At the investigated flutes with high fundamental frequencies and rather few partial tones, formants with fixed frequencies across the tone scale did not show any significant contribution.
The tone-to-tone variability of sound of the Boehm flute is not as uniform as its acoustic properties might suggest. Transverse flutes and recorders can be distinguished by octavial versus duodecimal (chalumeau-like) spectra, although this does not apply to each single tone. The recorder is a unique instrument with unique properties and expressions. Even besides temporal effects like the onset behaviour, simply by analysing the steady-state condition it shows its specific timbre characteristics. Further clarification is needed with view to the relation between variability of timbre and music aesthetics of the respective era and to its significance for HIP.

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