Expressive Musical Timing

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Abstract. Timing is crucial for the quality of expressive music performances. It is a means to mediate musical form and largely effects the emotive and motor characterization of a piece. Different epochs of music history do not only differ in their compositional styles but also caused change processes in performance practise.
To facilitate musicological investigations in historically informed performances and their changes, especially in the late baroque period, we had to create a software tool—less an autonomous performance system, rather a high-level performance editing system. Flexible formal models for performative features should allow to explore the parameter spaces and to simulate and evaluate a broad variety of styles: reserved baroque, affective romantic, unprecise beginners, and so on.
This paper focusses on the timing aspects of musical performances. We identified four general feature classes, namely tempo, rubato, constant asynchrony and human imprecision. To explore their degrees of freedom we ran a number of evaluations of professional recordings, live performances, and experimental recordings. On this basis we elaborate adequate formal models and describe their implementation within a MIDI-based performance system.

1 Introduction

To investigate differences and change processes of performance practice in music history we developed a software tool to model different performative styles. A major design element for this is human musical timing [10]. Performance practices have been investigated largely from the romantic era up to contemporary music [16, 17, 19, 20]. However, these findings were hardly transferable to historically informed performance of previous stylistic periods.

Existing performance systems turned out to be less applicable for the musicological task that rather necessitates a kind of a high-level performance editing system than an autonomous performance system [4, 11, 21, 22]. This text reports of our own investigations especially into the temporal aspects of expressive music performance and their synthesis.

In a performance analysis and evaluation phase we explored the shape and characteristics of performative features and how they change according to the structural and stylistic contexts (analysis by synthesis and measurement). On this basis we developed flexible formal models to describe and resynthesize these features within computer performances.

With these tools it is possible to support music production, e.g., in sound studios, for performance synthesis, film and game scoring. It is useful to demonstrate the development of historical performance practices and also to facilitate further investigations of music history, e.g., the interrelation between the development of music theory, organology and performance practice.

This paper is structured as follows: Section 2 will introduce the basic timing concept and corresponding definitions. In Section 3 we review and summarize our evaluation of skilled musicians. Sections 4 and 5 detail the formal models and their implementation which derive from the performance analyses. Section 6 provides a conclusion and exposes future perspectives.

2 Timing Features

Expressive musical timing is a complex interplay of multiple aspects. To facilitate a flexible simulation and reasonable parameterization, all timing aspects have to be separated and treated independently from each other.

This claim led to a phenomenon-based concept of musical timing: Singular features are individually shaped derivatives of a general class. The individual characteristics are adjusted according to the musical context of their application and the compositional and performative style. We identified four such feature classes:

Tempo describes the basic beat count per time unit (e.g., 100 beats per minute) that establishes the musical meter. It can remain constant, change discretely or continuously over time. Continuous tempo changes rarely feature a linear shape. The active work with tempo changes is important for the figuration of climaxes, melodic destinations, and musical phrases. Thus, it is applied over segments with musically medium-term and long-term extent, hence *macro timing*.

Rubato Musical meter is rarely performed exactly. Little prolongations and compressions are used consciously and subconsciously to express figures, motifs, metric accentuations, peak tones etc. Accordingly, rubato defines musically short-term timing deviations that take place within clearly delimited frames. Any deviations also have to be compensated within the same timeframe to keep up with the basic tempo. For that reason they are called *balanced deviations*. These occur as singular phenomenons but more often as repetitive schemes (e.g., in the Viennese waltz).

Constant Asynchrony Different onsets between musicians in an ensemble do often show systematic behaviour. It is originated in the hierarchy of instruments in the score (leading parts are ahead) and is affected in its extent by the overall tempo [14].

Human Imprecision Within the analyses deviations occur that cannot definitely be traced to a systematic reason. Even if effects of fingering, shifting, and room acoustics are taken into account, a rest of imprecision remains.

To determine appropriate parameter settings for particular musical contexts and styles we carried out a number of performance evaluations as described in the following.

3 Analysis and Retrieval

The parameter spaces defined in the previous section were discovered by an analysis of live, studio, and experimental recordings.

3.1 Methodology

The studio recordings were represented by 10 professionally produced recordings of G. P. Telemann's Trumpet Concerto in d major (TWV 51:D7). This chamber concert is one of the most famous baroque concerts for trumpet and typical in its form [7]. After a global analysis of tempo changes we focused on the first six bars of the first movement, the adagio. There, the most tempo changes emerged, leading us to assume a possible phrase-dependent performance. We also present results of rubato analyses, using the example of three motific groups of four sixteenth notes.

The live recordings were made during the *5th International Telemann Competition for historical woodwind instruments* (recorder, baroque flute and baroque oboe). The advantage was that all interpretations played live and no recordings were improved afterwards. In addition, the recording equipment (AKG C 1000 microphones and Zoom Handy H4 recorder) as well as its position and the room all recordings were made in, were the same. An international jury selected 15 players for recorder, who all studied or had been studying historically informed performance. We analyzed the compulsory piece, the sonata in f minor for recorder and basso continuo (from Telemann's "Der getreue Music Meister"). In the first movement, signed Triste, all performers played very distinct rubati.

In the experimental recordings 10 professional musicians for classical music as well as experts in historically informed performance played baroque and modern instruments (brass, strings and woodwinds). To get results that are free of any further contextual influences, they performed ritardandi and accelerandi on non-melodic tone repetitions.

Beats and onsets were detected in two steps, which combined automatic onset detection and human tapping. The automatic onset detection generated a number of onset hypotheses based on algorithms described by Duxbury et al [2], the power over time of an audio signal[1] and changes in energy between various frequency bands in a sequence of spectra[2] [1]. These were hypotheses for single onsets and also for onsets, which are of secondary relevance (e.g., arpeggiated cembalo play). By tapping, we set markers within the hypothesis space. These markers provided clues to identify the most valid hypotheses which were used for tempo and rubato analyses.

3.2 Results of Tempo Analyses

Every performance of the Trumpet Concerto showed outstanding deviations in timing to mark phrase boundaries. However, we could not find any evidence for permanent tempo changes over a long period of time. To evaluate whether successive deviations in note lengths can be described with a curve, we approximated the successive deviations with linear, quadratic and cubic functions in the first six bars of the adagio. Only two performances showed a significance of $\alpha > 0.05$ with the cubic function as the best fitting one, followed by the quadratic function.

In contrast to the phrase arch performance, which consists of an acceleration to a turning point and a slowdown until the end of a phrase, we could neither detect tempo changes over the whole phrase, nor an acceleration to a turning point (only for one out of ten

[1] http://sv.mazurka.org.uk/MzPowerCurve

[2] http://mazurka.org.uk/software/sv/plugin/MzSpectralFlux/

	interpreter I			interpreter II		
	R^2	F	α	R^2	F	α
linear	.43	6.75	**.029**	-	-	-
quadr.	.61	6.42	**.022**	.74	11.15	**.005**
cubic	.62	6.54	**.021**	.74	11.13	**.005**
	interpreter III			interpreter IV		
quadr.	.72	1.28	**.006**	.70	9.27	**.008**
cubic	.73	1.62	**.006**	.70	9.49	**.008**
	interpreter V					
linear	.34	4.74	.06			

Table 1: Approximated curves for the retard in bar six of the adagio. quadr.= quadratic function. 5 performers (not listed) did not show any significant values.

performers we could not exclude acceleration—linear with a weak correlation coefficient $R^2 = 0.12$ at the significance level $\alpha > 0.05$). Yet we found evidence for a gradual retard, albeit limited to the last bar of the phrase. Table 1 shows 5 of 10 performances. For interpreter V a linear retard could not be excluded. The interpreters I–IV played a retard, describing a cubic or a quadratic function, respectively. These findings match with previous studies of retard [5, 9].

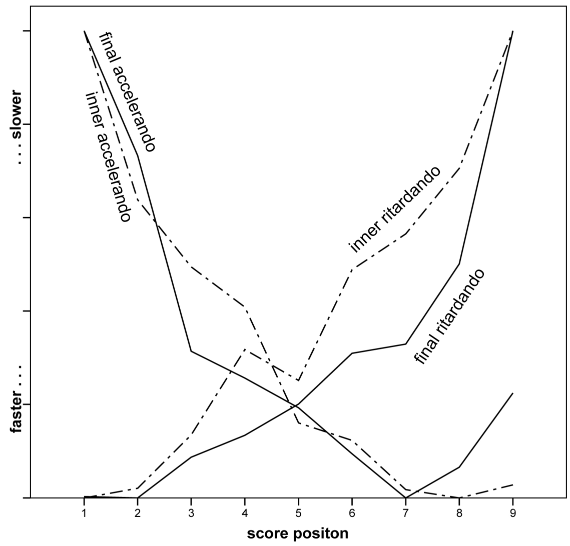

Figure 1: Experimental performances of accenerandi and ritardandi: Final characteristics are more curved than in a piece.

First Half and Second Half Characteristics

To extract ritardandi and accelerandi separately, we analysed the experimental recordings, which had no musical context to the greatest possible extent. Although all musicians were experts, they found these context-free scores hard to play. Some had difficulties to count the bars, some played faster instead of slower or had a lot of questions about the differences in timing. All musicians performed additional deviations on metrical accents, which (sometimes in high degree) distorted the accelerandi and ritardandi. In the analysis the performers showed less problems in playing a ritardando, especially the final retard. The standard deviations of all performances for the final retard (mean $SD = 14\%$ of the entire tempo change) were less than for the inner-piece retard (mean $SD = 17\%$).

Moreover, the quadratic shape of the final retard had a higher degree than the inner one which was weakly curved. However, the larger part of the tempo changes still took place in the second half of the whole process.

In contrast to the ritardandi, the larger part of accelerandi took place in the first half. Both, final and inner accelerandi showed a logarithmic shape, both with a mean $SD = 17\%$ and a weaker curvature for the inner accelerandi. This corresponds to the distinction of inner and final ritardandi (see Figure 1).

3.3 Results of Rubato Analyses

Differences in Deviations

Adagio						
contour	**lsll**	lsls	lssl	slsl	other	$\sum$
occurrence	**11**	6	4	3	6	30
Triste						
contour	lsll	lsls	**lssl**	lsss	other	$\sum$
occurrence	9	3	**13**	5	0	30

Table 2: Different relations in a group of four sixteenth notes in the Trumpet Concerto (Adagio) and sonata for recorder (Triste). l=long, s=short

Deviations in note lengths are restricted to the bar level or shorter. In his pioneering work, Quantz [12] recommended to lengthen the first and third note in a group of four sixteenth notes in a slow tempo. At a fast tempo only the first of four notes has to be lengthened, but beside these rules everything has to be played under the major premis of *diversity*[3].

[3]The connection between Telemann and Quantz as well as other contemporary musicians has been proven recently [8, 13, 15].

During the first six bars of the adagio, groups of four sixteenth notes occur three times, so 30 examples have been available from the studio recordings. As shown in Table 2, the performers played different relations of these four notes, mostly in the way *long-short-long-long* (*lsll*), followed by *long-short-long-short* (*lsls*). Differences in contour as well as in markedness refer to the intention of variety of performance. A few exceptions gave a view on a random error: Interpreters, who intended to play the same rubato, match with a minimal accuracy of 12ms. In the experimental recordings many performances varied to an unexpectedly small extent of less than one percent of the underlying meter. Within this amount errors of measurement and performance noise could not be clearly differentiated.

First-Note-Lengthening

	lssl			*lsll*		
	R^2	F	α	R^2	F	α
lin.	.985	195	**.0008**	.989	261	**.0005**
log.	.983	169	**.0010**	.971	102	**.0020**
pow.	.983	172	**.0010**	.985	193	**.0008**

Table 3: Best fitting curves for the rubato over four sixteenth notes in the Triste. lin.=linear, log.= logarithmic, pow.= power function. l=long, s=short

More obvious results we found in the live recordings of the Triste movement. Here, two groups of four sixteenth notes occur and are performed by 15 interpreters. As seen in Table 2, for most of the part the contour *long-short-short-long* (*lssl*) was performed.[4]

A definite result has been the lengthening of the first note. Compared to the mean deviations of the last three sixteenths, the first was played from 15% up to 140% longer (with mean $\bar{x} = 66\%$ and $SD = 28\%$). Nevertheless, the high variation of the first note shows its outstanding position. This can also be seen in Figure 2, were the accumulated intervals are shown. The lengthening of the first note results in a maximum deflection of the performance curve, referring to an assumed equal play.

The most frequent contours *lssl* and *lsll* in the recorder sonata (see Table 2) were approximated separately, as demonstrated in Table 3. As the curve does not describe the relative deviations, the logarithmic function as well as the linear and power function fit best. Apart from the statistical relevance of these findings, the logarithmic function has to be preferred: A

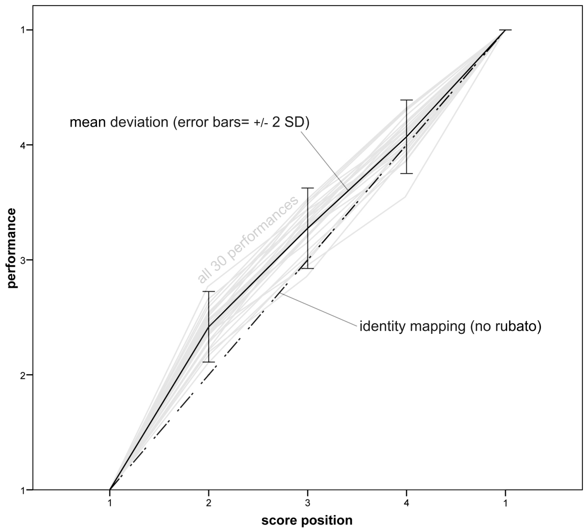

Figure 2: Rubato over four sexteenth notes in the Triste movement.

linear function would describe an exact equal playing that was excluded because of the above-mentioned results. The power curve just overlaid the linear one (with marginal deviations in a more unfavourable direction than the mean curve), and therefore has to be excluded as well.

The often found *last-note-lengthening* [3, 4] depends on the importance of the following first note. In the Triste the last notes have been played longer at the end of the phrase. Therefore, the last note should not be seen as a lengthened note. It rather has to be seen as an additional pause before the following phrase or figure.

In the late nineteenth century, Riemann [18] sowed the seed with his rules of agogic from which contemporary performances developed and still refer to, respectively. In this regard, we discovered differences, exemplified on historically informed performance. They concern tempo and rubato features, their shape characteristic and intensity. Thus, a synthetic performance must guarantee the flexibility in rubato and also tempo, particularly the various shapes and curvatures. In the following we will describe our approach to this.

4 Macro Timing

For the formalization and implementation of timing features we decided to keep the macro-micro distinction. This Section will focus on macro timing and describe our approach to modeling expressive musical tempo within a performance system. In order to support the huge amount of characteristics, as discovered

[4]It has to be mentioned that the cembalist decides the length of the last sixteenth note, and therefore if it will become *long* or *short*. The recorder only plays four sixteenth notes and ends in a pause, filled by the continuo.

previously, we present an extended tempo representation and corresponding implementational details for an adequate playback.

Since the MIDI standard is still present and extensively supported by home computer systems as well as by professional music and studio hard- and software we decided to base our implementations on the MIDI protocol, too. Therefore, we applied the MidiShare engine [6], which provides a low-level MIDI-API and a real-time scheduling system for MIDI events. The new tempo map formalism, which is described below, was implemented as an XML data structure.

4.1 Formalization

Musical tempo features are represented as tempo instructions T. These are listed in the *tempo map* M_T in timely increasing order:

$$M_T = (T_0, T_1, ..., T_n)$$

Each instruction T_m $(0 \leq m \leq n)$ is a 5-tuple

$$T_m = (d_m, t_{1_m}, t_{2_m}, b_m, i_m)$$

with d_m providing the tempo-independent date of the instruction within the piece of music. This can be, e.g., a MIDI ticks value, as used here, or it can follow the Bar-Beat-Unit convention. Both are equivalent and can easily be converted using the ticks-per-quarter-note value (henceforth *clicks*) which is provided by each MIDI file header.

While d_m marks the beginning of the tempo instruction T_m, its range is terminated either by d_{m+1} of the succeeding instruction T_{m+1} or, in case of T_m already being the last instruction in M_T, by the date of the last event within the piece of music.

Within this range, T_m defines a continuous tempo transition from tempo t_{1_m} to t_{2_m} (both measured in beats per minute). Therefore, b_m provides the *musical length* of one beat in floating point format (e.g., quarter note: $1/4 \rightarrow 0.25$, half note: $1/2 \rightarrow 0.5$ and so forth).

To model the different tempo transition characteristics, as discovered in Section 3, the usually linear transition is twisted via a potential function in the domain $[0; 1]$ (corresponds with the degree of tempo change). The exponent given by i_m $(i_m \in \mathbb{R}, i_m \geq 0)$ steers the deflection of the function:

$i_m = 0$ to ignore t_{1_m} and run t_{2_m} immediately (subito) as constant tempo,

$0 < i_m < 1$ for first half characteristics,

$i_m = 1$ to achieve the mechanical linear behavior,

$i_m > 1$ for second half characteristics.

The intensity of the ritardando/accelerando grows the more the transition deflects from the linear course. Extreme deviations approach a subito-like behaviour.

4.2 Implementation

The MIDI standard only defines constant tempi and discrete, i.e. stepwise, tempo changes. Seemingly continuous transitions can be achieved by discretization with sufficiently small step heights and with step lengths of at least the shortest inter-event distance. However, the high-level representation of tempo instructions gets lost. The result is still only an approximation and subject to more or less audible aliasing effects (abrupt/bouncy tempo changes).

To overcome these limitations, the MIDI internal tempo map is ignored and substituted by our new macro-timing representation, which is provided by an XML file accompanying the MIDI data. According to these information, the milliseconds date of each MIDI event is determined by function $\mathrm{ms}(d)$ before sending it to the scheduler (with d being the MIDI ticks value to be converted):

$$\mathrm{ms}(d) = \begin{cases} d & : \ d \leq d_0 \\ \mathrm{con}_1(d - d_m) + \mathrm{ms}(d_{m-1}) & : \ t_{1_m} = t_{2_m} \\ \mathrm{tran}(d - d_m) + \mathrm{ms}(d_{m-1}) & : \ \text{otherwise} \end{cases}$$

for m as the index of tempo instruction T_m which holds:

$$d_m < d \leq d_{m+1}$$

with d_{m+1} as the tick date of instruction T_{m+1} or of the last event if T_m has no successor in the tempo map.

In case of a constant tempo, i.e. t_{1_m} equals t_{2_m}, the conversion is easily done by function $\mathrm{con}_k(d_l)$ with $d_l = d - d_m$ being the local MIDI ticks position within the range of T_m and $k \in \{1; 2\}$:

$$\mathrm{con}_k(d_l) = \frac{60000 \cdot d_l}{t_{k_m} \cdot 4 \cdot b_m \cdot \mathit{clicks}}$$

Otherwise, T_m defines a substantial tempo transition. Therefore, the conversion is done by function $\mathrm{tran}(d_l)$:

$$\mathrm{tran}(d_l) = \mathrm{con}_1(d_l) + \frac{(\mathrm{con}_2(d_l) - \mathrm{con}_1(d_l)) \cdot d_l^{i_m+1}}{(i_m + 1)(d_{m+1} - d_m)^{i_m+1}}$$

The result of function $\mathrm{ms}(d)$ added to the milliseconds date when the playback begin. Since all musical parts/MIDI tracks are processed individually, this date is also a basis for synchronization to compensate numerical imprecision. The sounding result is a proper aliasing-free tempo transition.

In our implementation we furthermore distinguish between global and local tempo maps. The global ones constitute a universal timing base for all tracks. Local tempo maps, by contrast, only provide the macro-timing base for one track. Local information dominate the global, accordingly, the global tempo map is ignored if there is a local one.

5 Micro Timing

Micro-level timing features add fine-structured details to the macro-timing curve. They often show a repetitive or irregular but continual behavior.

5.1 Formalization

Micro-level timing features have to be differentiated as those with systematic and those with apparently random behavior. Both can change over time; imprecise ensemble play can, e.g., be originated in a situation within the composition which is technically difficult to realize. As a result, both feature types are to be organized as dated entries within ordered lists M_S (systematic deviations) and M_R (random imprecision).

Systematic Deviations

Rubati and constant deviations are both of systematic type, hence, summarized into one formalism (m is the index of the M_S list entry):

$$S_m = (d_m, f_m, r_{1_m}, r_{2_m}, i_m, c_m)$$

In correspondence to the tempo formalism (see Section 4) d_m indicates the tempo-independent date (in MIDI ticks) from when on the micro-level deviations are to be applied. It is terminated by d_{m+1}.

The simplest kind of deviation, the *constant asynchrony*, is a plain delay. Its value is given by attribute c_m in milliseconds ($c_m \in \mathbb{Z}$).

All remaining attributes define the *rubato deviation scheme* (see Figure 3) which is continuously applied to all consecutive timeframes of length f_m (in ticks). One timeframe may, e.g., cover the length of a measure, a figure, or even less. Since all rubato deviations have to compensate within the same frame, f_m also defines the meter of overall synchrony. Consequently, the *rubato deviation scheme* must be a mapping of metrical time to rubato time in the domain $[0; f_m)$.

The potential function in $[0; 1)$ again turned out to provide a sufficient behaviour. So the timeframe was scaled down to this domain. Exponent i_m controls whether the time has to:

- be stretched in the beginning and compressed in the end ($0 < i_m < 1$),
- be accelerated in the beginning and stretched in the end ($i_m > 1$), or
- remain unchanged ($i_m = 1$).

An initial non-negative delay can be set by r_{1_m}. Correspondingly, r_{2_m} sets the arrival at the end of the frame early. Both attributes indicate a relative position within the timeframe and have to hold the following condition:

$$0 \leq r_{1_m} < r_{2_m} \leq 1; r_{1_m}, r_{2_m} \in \mathbb{R}$$

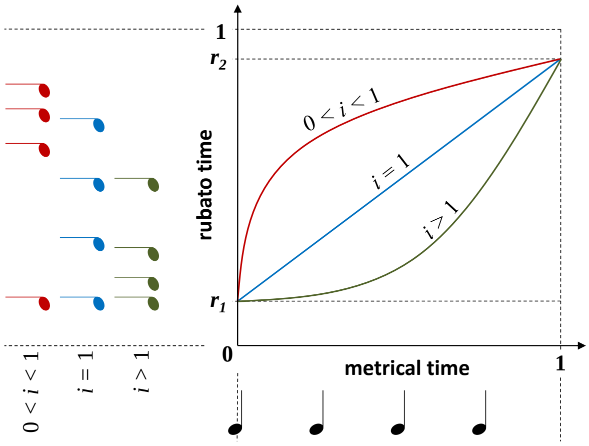

Figure 3: Three *rubato deviation schemes* for a timeframe of four quarter notes with different settings for i.

Random Imprecision

Up to now, the performance is perfect regarding macro and micro timing. Nevertheless, human musicians are rarely able to perform all nuances perfectly. Even extensively trained professionals are subject to psychological and motor conditions which introduce a gaussian distribution into the accuracy of micro timing.

Friberg's KTH rule system implements this *performance noise* by two components: the musician's motor delay and long term tempo drifts [4]. The latter, i.e., long term tempo drifts, have to be classified as macro-timing features (see Section 4). Human imprecision causing micro deviations, however, have to be applied and parameterized more carefully to measure up with the qualitative aspects of player's aptitude.

It can change over time according to the musical context and technical difficulty. Thus, we organize these deviations as dated information in an ordered list M_R. An entry

$$R_m = (d_m, \sigma_m)$$

defines the normal distribution around the exact milliseconds date of all note events in $[d_m; d_{m+1})$ with a standard deviation of σ_m (in milliseconds).

5.2 Implementation

To get the definite milliseconds date for each note event, all micro-timing deviations have to be added to the macro timing. The whole sequence of date transformations is illustrated in Figure 4.

For numerical reasons, the rubato transformation is already applied to the tempo-independent tick date by

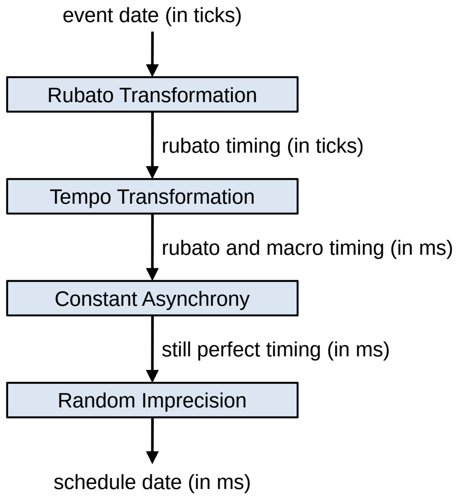

Figure 4: The complete date conversion pipeline.

function rub(d) with d as the tick date to be transformed.

$$\text{rub}(d) = \left[\left(\frac{\text{lp}(d)}{f_m} \right)^{i_m} \cdot (r_{2_m} - r_{1_m}) + r_{1_m} \right] \cdot f_m + d_f$$

Once again, the index m refers to the entry in M_S with date $d_m < d \leq d_{m+1}$, i.e., the last entry before d. Function lp(d) determines the local position of d within its timeframe

$$\text{lp}(d) = (d - d_m) \text{mod} f_m$$

and d_f is the date of that timeframe $d_f = d - \text{lp}(d)$.

All remaining micro-timing features are applied after the tempo-based conversion from ticks into millisecond dates. The *constant asynchrony* c_m is also a millisecond value, and is simply added.

A random imprecision with standard deviation σ_m is added to the resulting precisely timed date. While all previous transformations were keeping the order of events, this last step runs the risk of causing inconsistencies (e.g., a note-on event delays after its corresponding note-off). Before adding the random deviation, a consistency check has to prevent this situation.

Altogether, the definite milliseconds timing of tick date d, timing(d), is done as follows:

$$\text{timing}(d) = \text{ms}(\text{rub}(d)) + c_m + \text{rand}(\sigma_m)$$

We already differentiated macro timing as global or local. Likewise, both micro-timing feature maps M_S and M_R can be defined globally for all parts or locally per part in order to get lively performances with musicians who play more or less well together and exact.

6 Conclusion and Future Perspectives

This paper traced our investigations into expressive musical performances with regard to timing aspects. We identified four different classes of timing phenomenons, namely tempo, rubato, constant deviations and random imprecision.

Our evaluations have shown that these features cannot be applied statically. In different musical contexts and performance styles they showed very distinctive characteristics that we wanted to introduce into computer performed music. Therefore, we developed adequate formalizations that we implemented within a performance system.

However, knowledge about the tools of expressive performances does not represent knowledge about their application. As mentioned, the characteristics of all timing features vary according to the musical context. Thus, one direction of our future work will be to investigate the association of structural and performative features and their characteristics.

In the context of historically informed performances our models do already provide valuable quantitative information which allow a better insight into performance practices, and how they changed in history.

Moreover, timing is only one of many aspects that expressive music performance deals with. Our future research will also include the analysis of dynamics, i.e. loudness, and articulation.

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References

[1] S. Dixon. Onset Detection Revisited. In *Proc. of the 9th Conf. on Digital Audio Effects (DAFx-06)*, pages 18–20, Montreal, Canada, Sept. 2006.

[2] C. Duxbury, J. P. Bello, M. Davies, and M. Sandler. Complex Domain Onset Detection for Musical Signals. In *Proc. of the 6th Conf. on Digital Audio Effects (DAFx-03)*, London, UK, Sept. 2003.

[3] A. Friberg. *A Quantitative Rule System for Musical Expression.* PhD thesis, Royal Institute of Technology, Sweden, 1995.

[4] A. Friberg, R. Bresin, and J. Sundberg. Overview of the KTH Rule System for Musical Performance. *Advances in Cognitive Psychology, Special Issue on Music Performance*, 2(2–3):145–161, July 2006.

[5] A. Friberg and J. Sundberg. Does Music Performance Allude to Locomotion? A Model of Final Ritardandi Derived from Measurements of Stopping Runners. *The Journal of the Acoustical Society of America*, 105(3):1469–1484, March 1999.

[6] GRAME. *MidiShare Developer Documentation*. Computer Music Research Lab., France, 1.91 edition, Jan. 2006.

[7] W. Hirschmann. Telemann, Georg Philipp—Die Konzerte. In I. Allihn, editor, *Barockmusikführer Instrumentalmusik 1550–1770*, pages 450–454. Metzler und Bärenreiter, 2001.

[8] W. Hobohm. *Berührungspunkte in den Biografien Georg Philipp Telemanns und Johann Sebastian Bachs sowie ihrer Familien*, volume 18 of *Magdeburger Telemann-Studien*, chapter 1. Georg Olms, Hildesheim, Zürich, New York, 2005.

[9] H. Honing. The Final Retard: On Music, Motion, and Kinematic Models. *Computer Music Journal*, 27(3):66–72, 2003.

[10] P. N. Juslin. Cue Utilisation in Communication of Emotion in Music Performance: Relating Performance to Perception. *Journal of Experimental Psychology: Human Perception and Performance*, 26(6):1797–1813, 2000.

[11] G. Milmeister. *The Rubato Composer Software: Component-Based Implementation of a Functional Concept Architecture*. PhD thesis, Mathematisch-naturwissenschaftliche Fakultät der Universität Zürich, 2006.

[12] J. J. Quantz. *Versuch einer Anweisung die Flöte traversière zu spielen*. Bärenreiter, reprint (1997) edition, 1752.

[13] J. J. Quantz. *Brief an Telemann vom 11. Januar 1753*, pages 364–366. VEB Deutscher Verlag für Musik, Leipzig, Germany, 1972.

[14] R. A. Rasch. Synchronisation in Performed Ensemble Music. *Acustica*, 43:121–131, 1979.

[15] R.-J. Reipsch. Zur Rezeption von Telemanns Kompositionen für Traversflöte im Umfeld von Quantz—Neues aus dem Notenarchiv der Sing-Akademie zu Berlin. In B. E. H. Schmuhl and U. Omonsky, editors, *34. Wissenschaftliche Arbeitstagung Michaelstein 2006—Zur Flötenmusik in Geschichte und Aufführungspraxis von 1650 bis 1850*, Michaelstein, Germany, 2009.

[16] B. H. Repp. Diversity and Commonality in Music Performance: An Analysis of Timing Microstructure in Schumann's "Träumerei". *Journal of the Acoustical Society of America*, 92(5):2546–2568, 1992.

[17] B. H. Repp. A Microcosm of Musical Expression. I. Quantitative Analysis of Pianists' Timing in the Initial Measures of Chopin's Etude in E major. *The Journal of the Acoustical Society of America*, 104(2):1085–1100, 1998.

[18] H. Riemann. *Musikalische Dynamik und Agogik, Lehrbuch der musikalischen Phrasierung auf Grund einer Revision der Lehre von der musikalischen Metrik und Rhythmik*. Hamburg, Germany, 1884.

[19] N. P. M. Todd. The dynamics of dynamics: A model of musical expression. *The Journal of the Acoustical Society of America*, 91(6):3540–3550, 1992.

[20] M. M. Wanderley and C. Cadoz. Gesture-Music. In M. M. Wanderley and M. Battier, editors, *Trends in Gestural Control of Music*, pages 71–86. Ircam, Centre Pompidou, 2000.

[21] G. Widmer and W. Goebel. Computational Models of Expressive Music Performance: The State of the Art. *Journal of New Music Research*, 33(3):203–216, Sept. 2004.

[22] G. Widmer and A. Tobudic. Playing Mozart by Analogy: Learning Multi-Level Timing and Dynamics Strategies. *Journal of New Music Research*, 32(3):259–268, Sept. 2003.