Expressive Articulation for Synthetic Music Performances

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ABSTRACT

As one of the main expressive feature in music, articulation affects a wide range of tone attributes. Based on experimental recordings we analyzed human articulation in the late Baroque style. The results are useful for both the understanding of historically informed performance practices and further progress in synthetic performance generation. This paper reports of our findings and the implementation in a performance system. Because of its flexibility and universality the system allows more than Baroque articulation.

Keywords

Expressive Performance, Articulation, Historically Informed Performance

1. INTRODUCTION

Humans achieve expression in music performances by several features. Whatever is additionally named by different authors[12, 15, 5], all of them conform to three expressive features, which are timing, dynamics (loudness) and articulation [10].

Today's performance systems established articulation as tone duration [15], sometimes reduced to the span between *legato* and *staccato* [7] or *non-legato* [13]. In this respect expressive articulation was measured [8, 14] and also implemented into expressive performance rule systems [4].

Duration is indeed the most striking feature of articulation but is not its only one. Articulation describes the forming of a tone in all its facets. This also includes loudness, timbre, intonation, and envelope characteristics.

This paper aims at three major tasks concerning expressive articulation: First, articulation is supposed to influence duration, but all remaining tone features like loudness, timbre, intonation, and envelope characteristics as well. Section 2 introduces the whole range of these aspects. Based on the first task, Section 3 shows our method demonstrating that different articulations change these tone features. The analysis exemplifies Baroque articulation. Consequently, Section 4 describes the implementation of articulation features including the possibility to freely define further articulation styles. A conclusion follows in Section 5.

NIME2010, June 15-18, 2010, Sydney, Australia.

2. WHAT IS ARTICULATION?

To trace the meaning of articulation it is first necessary to be aware of the difference between the notation of music and its actual performance. Throughout this article the terms 'note' and 'tone' are strictly distinguished. A note is a symbol of a musical event. Its attributes indicate pitch, length, loudness, onset and timbre (instrumentation). A tone, by contrast, is the actual physical event in a performance. Its attributes are pitch, duration and so forth that all correspond to the referring indications of the note. Expression in music performance touches deviations from tone attributes and note indications. Both timing and dynamics shape musical structure by influencing tone onsets and loudness values, respectively. Articulation as the forming of the single tone adds further deviations (e.g., an accent on a crescendo). This concerns all tone features, which are loudness, pitch, duration, envelope, and also timbre. The following description briefly introduces the parameter space articulation is involved in.

Envelope: A tone can consist of the four parts attack, decay, sustain and release. Every part can show different proportions or even be absent. On the whole they describe the loudness progression over a single tone.

Duration: It is the time from tone-onset to its offset, either proportional to the inter onset interval (IOI) or in absolute time.

Loudness Deviations: Independently from the dynamic shape of a musical section, certain articulations influence loudness.

Timbre Deviations: Some articulation instructions particularly refer to playing techniques (*pizzicato*, hammered bow strokes). They affect timbre changes that are neither exclusively caused by loudness changes nor depend on instrumentation.

Intonation Deviations: Similar to loudness and timbre, different articulations may influence intonation [9].

Articulation can affect one or more of these tone features. The following Section shows the analysis of envelope, tone duration, and loudness deviations.

3. MEASURING ARTICULATION

The meaning of articulations changed with time and place. We therefore considered a stylistic homogeneity. In addition, we wanted to choose key articulations for testing. The focus on German late Baroque/early Classic music fulfilled both conditions; it reduced the range of interpretation and, on the other hand, supports articulations that are both reasonable and still valid today [1, 18].

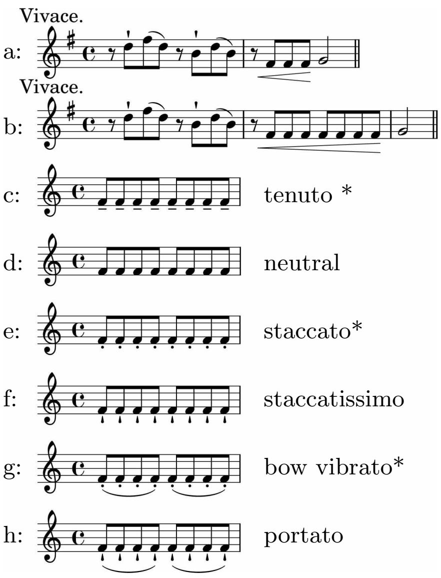

Figure 1: Exercises from Mozart: a(original) and b(experimental); Reichardt: d-h; *: additional.

3.1 Methodology

Figure 1 shows all articulations that were analyzed. They are described as follows [1, 17, 18, 19]:

tenuto: Tones are to play as long as possible but clearly separated from each other.

neutral: If notes are without any annotation it is to decide how to articulate them. This depends on the respective common practice. The analysis refers to a prominent example in Baroque music: Eighths (quavers) in the accompaniment are played short [17, 19].

staccato/staccatissimo: It means very short/ as short as possible.

bow vibrato: [1] All notes under a slur are played by a continuous increasing and decreasing bow pressure but without any stopping of the bow stroke.

portato: [1] All notes under a slur are played with one bow stroke but clearly separated by stopping the bow.

Because most standard Baroque articulation instructions emphasize duration, two special articulations with an emphasis on (string) playing technique were added (Figure 1g and h).

We recorded ten professional musicians playing Baroque and modern instruments; altogether we recorded 14 different instruments, including strings, brass and woodwinds. The exercises followed eighteenth century articulation practises that had been taken from two major treatises on violin playing: Johann Friedrich Reichardt [19], i.e., Reichardt exercise, and Leopold Mozart [17], i.e. Mozart exercise, as shown in Figure 1.

Two AKG 1000 microphones were placed two meters in front of the instrument. A larger distance would have entailed less loudness differences and increased recorded reverberation. On the contrary, a closer position would carry the risk that body movements influence the position of the instrument. Regarding the directional characteristics of instruments, this would have affected the recorded loudness values too much. Being aware that recorded decibel values depend on all recording conditions, we ran a dynamic range test with the same setting. So all decibel values additionally were analyzed proportionally to the *piano – forte* range. Tone onsets were extracted automatically by using the Sonic Visualiser[2] and onset detection algorithms based on energy changes in frequency bands as well as power fluctuations described by Duxbury et. al [6]. Missing and mismatched onsets were manually revised, for instance, if no or more than one onset were found on a single tone. Recordings were excluded, if musicians misinterpreted the annotations or were not able to perform them (the *bow-vibrato* is a particular string annotation, so brass or woodwind instruments were not recorded).

[1]Both annotations differ in Baroque string playing [16, 17] and largely in later epochs. The definition refers to the experimental exercises.

articulation	max percentile			offset percentile		
	25	50	75	25	50	75
tenuto	.363	.661	.780	.799	.893	.963
neutral	.339	.469	.586	.692	.771	.876
bow vibrato	.413	.495	.571	.693	.780	.812
portato	*71*	*95*	*124*	.533	.727	.769
staccato	*73*	*87*	*101*	.532	.567	.744
				160	*173*	*225*
staccatissimo	*60*	*80*	*102*	.466	.523	.624
				143	*161*	*189*

Table 1: Loudness distributions show time proportions to IOI, except italic letters that are ms values.

In the Reichardt exercises (see Figure 1c–h) all tones that belonged to the same articulation were averaged for every recorded instrument (see Figure 2). Envelope differences, release phase and reverberation impeded a definite offset detection. To indicate offsets we decided to label an offset marker where the loudness falls below 66 percent of the particular loudness range of the particular mean articulation. There the loudness decreased intensely but the signal was obviously not disrupted by reverberation. Figure 2 shows the offset markers for all averaged articulations that were played by one musician with one string instrument. Even if the offset marker and the real offset point differed, most articulations could be distinguished by the offset markers. In addition to onset and offset markers, we inserted maximum markers where the maximum loudness was reached. The combined onset, maximum and offset markers allowed a clear distinction of all tested articulations.

3.2 Results

The results taken from the experimental recordings concern duration, loudness and envelope characteristics. In all tests no systematic differences were found between modern and Baroque instruments or between string, brass and woodwinds. Admittedly, modern instruments showed an increased maximum loudness value but no differences regarding the *piano–forte* range.

Duration

Table 1 summarizes the results of the Reichardt exercise. Every position of the maximum and offset markers was analyzed in absolute time (absolute condition) and proportionally to the IOI (proportional condition). With a comparison of the dispersion—represented by the interquartile range (IQR)—different time attributions were made: The

[2]`www.sonicvisualiser.org`

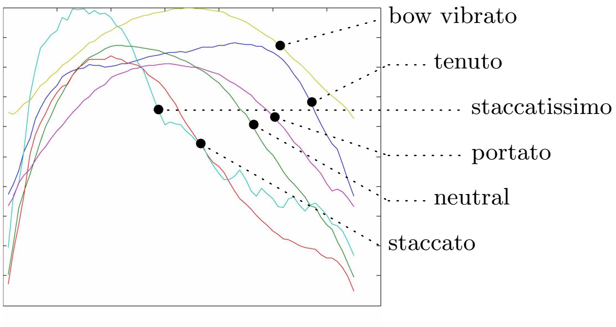

Figure 2: Mean envelopes for one performer playing a modern violin. Dots=offset markers.

duration of particular articulations can always be the same proportionally to the IOI or depend on absolute time. If the duration depends on the IOI, the IQR is smaller in the proportional condition than in the absolute condition. For example: *Legato* tones are defined to last 100 percent of the IOI. So the IQR in the proportional condition is zero, but the millisecond range, and therefore the dispersion for the absolute condition, would be as large as note values and tempi could ever be. *Tenuto*, *neutral*, and *bow vibrato* showed a smaller IQR in the proportional condition. Thus they depend on the IOI. On the contrary, we found smaller IQRs in the absolute condition for the *staccatissimo*, *staccato*, and *portato* with respect to the maximum. The offset IQR differences were very low for the *staccatissimo* and *staccato*[3], but the IQRs were still lower in the relative condition. A summary of the attributions is given in Table 2. If the IQR was smaller in the absolute condition, the values in Table 1 were given in milliseconds.

Loudness Deviation

The median loudness range from *piano* to *forte* was 21.4 dB. To detect general loudness differences in the Reichardt exercise, the mean loudness of every articulation was compared to the *neutral* mean loudness (see Table 3). As one can see, *staccatissimo* and *tenuto* were played louder than *neutral*.

In the Mozart exercise the first six notes were played in two different ways[4]: Figure 3 shows the median decibel values referring to the quietest tone for every of both accentuation concepts. The accent levels were similar to those being extracted from the Reichardt exercise. Remarkably, the last tones were played with a slightly crescendo in both versions.

The second bar of the Mozart exercise included a crescendo that in fact belongs to dynamics. Yet, we found changes in tone duration instead of loudness changes: Figure 5 shows two samples of a crescendo with a *staccato* articulation, taken from the second bar of the Mozart exercise. Unlike the violin, which continuously increases its loudness, the Baroque bassoon successively increased duration within the *staccato* range.

[3] IQR differences: *tenuto* = 0.39, *neutral* = 0.05 and *staccato* = 0.009.

[4] Two of the 14 recordings did not fit to one of these strategies and were excluded.

articulation	relation of time progression prop. to IOI	absolute time
legato & tenuto	max, off	att
portato	off	att, max
staccato & staccatissimo		att, max, off
bow vibrato	att, max, off	
envelope	prop.	absolute
attack, decay shape		X
long tone sustain	X	
short tone sustain		X
release		X

Table 2: Tone dependencies on time (prop=proportional, att=attack, max=maximum loudness, off=tone offset).

artic.	dB	%	artic.	dB	%
tenuto	1.62	*7.6*	neutral	-	-
staccato	-2.14	*-10.0*	staccatissimo	2.23	*10.4*
portato	-1.72	*-8.0*	bow vib.	-1.88	*-8.8*

Table 3: DB differences from *neutral* articulation (=artic.) and proportionally to *piano–forte* range.

Envelope

Table 1 shows the position of maximum loudness, which is the attack time of short tones. Long tones are different, for their maximum sustain loudness can be on a very late position and raise above the attack maximum. In the *portato* condition of the Reichardt exercise, the maximum marker (see Table 1) and loudness values (see Table 3) were quite similar to the *staccato* articulation, but its tone duration was closer to the *neutral* articulation (see Table 1).

Furthermore, there were cases of tones being as short as a *staccatissimo* or even shorter but with a clearer sound that resulted from a more concrete pitch and cleaner timbre: These were short tones bounded on previous *legato* tones (see Figure 4).

3.3 Discussion

Articulations differ not only in duration, though it is the most prominent feature. *Tenuto*, *staccato* and *staccatissimo* were discriminated by duration. Short articulations like the *staccatissimo* and also the *staccato* did not completely turn out to be proportional to the IOI. Further analysis should focus on this problem in particular, for it is not unthinkable that *staccato* and *staccatissimo* offsets depend on absolute time, which may be additionally influenced by the absolute IOI. Consequently, the *staccatissimo* as an "as short as possible" articulation showed an envelope nearly reduced to its attack and release. Thus, the fastest possible tempo in a *tenuto* articulation can be deduced from these differences: It is reached if the notes are as short as the *staccatissimo* attack (it corresponds to the maximum of 80ms, see Table 1) and at the same time correspond to the *tenuto* proportion. This is fulfilled by playing sixteenth notes at 167 quarter notes per minute. In his masterpiece on Baroque

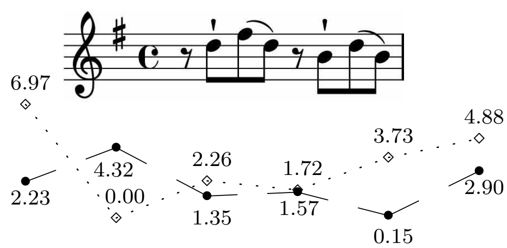

Figure 3: accentuation strategies (median dB values) for the first six notes of the Mozart exercise.

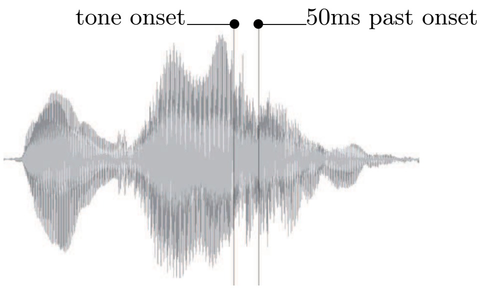

Figure 4: Tone transition from f♯ to d during the first bar of the Mozart exercise (see Figure 1).

flute playing, Johann J. Quantz [18], composer and flautist to King Friedrich II, wrote that the shortest notes should not be played faster than sixteenth notes in 150–170 quarter notes per minute!

The annotations *portato* and *bow vibrato* refer to playing technique rather than to tone duration. This mainly resulted in envelope differences. Independently from loudness, the attack transition is highly responsible for the tone character [20]. With a different playing technique the excitation of a tone gets modified, resulting in changes of the envelope and the perceived sound. However, the attack time is not the minimum limit. Short tones bounded on previous *legato* tones need no extra energy input to build up an attack. They take over the previous energy and only change pitch. This often occurs at the last note under a slur and can result in a very short duration (Figure 4).

Certainly, only the envelope was analyzed and no timbre deviations; indeed, it can be argued that timbre alters systematically with different articulations, too. This, of course, requires further investigations of timbre deviations as well as in pitch deviations.

Another finding concerned loudness: Being not as obvious as the duration feature, the analysis showed that articulations can also include accents. So the *staccatissimo* did in contrast to the *staccato*.

Furthermore, we found evidence for an interweaving of different expressive features, particularly articulation and dynamics: In a crescendo task (see Figure 5) the violin continuously increased loudness, whereas the Baroque bassoon rapidly reached its limits. Incapable to get louder, the musician increased the emerged energy sum by successively lengthening the tones. Normally, articulation is not the expressive feature responsible for a crescendo, but in this case it overtakes what dynamics cannot fulfil.

In addition, we were confronted with a slightly crescendo at the end of the first bar of the Mozart exercise. As an underlying cause the subsequent crescendo may explain this (see Figure 1b): The first tone of the second bar is the first tone of the crescendo and usually quieter than the previous. Consequently, this previous tone, which is the last tone of the first bar, has to become louder and therefore causes this slightly crescendo.

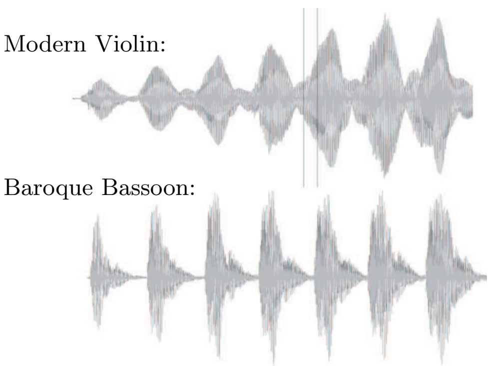

Figure 5: Crescendo from second bar of the Mozart exercise (see Figure 1).

The analysis was restricted to Baroque articulation. It is expected that differences in style have an effect on all values that were found in this study. However, stylistic differences will hardly revise the fact that articulation influences every tone feature.

From a musicological perspective, the analyzes serve as a first step towards a greater compilation of different articulation style phenomena. Future research should not only consider other styles but also focus on nuances of single articulations. Finally, the simulation of different performance styles shall offer a new approach for listening analyzis.

Therefore, it is a challenge for signal processing to extract deviations of timbre, pitch and offsets. To detect reliable offsets it is not suitable to restrict research to MIDI-instruments. One possibility might be to involve visual performance information.

The question of random fluctuations also remains unanswered. In this way progress can be achieved by interdisciplinary approaches, including further psychomotor discoveries.

4. IMPLEMENTATION

Articulating a note means more than changing its duration. The investigations described in the previous Section reveal, for instance, a very distinctive loudness component which did not derive from conventional dynamics or metrical accentuation.

Furthermore, all articulations are not created equal. Identical instructions are rendered differently in different stylistic or expressive contexts. It can even be inhomogeneous within one and the same style. A neutral articulation in a light-footed Baroque dance is shorter and more detached than in Baroque hymns. Moreover, the articulation vocabulary is not fixed. The basic articulations, as introduced and analyzed in the previous Section, were established in the Baroque era. The Romantic period and Serialism, however, invented a lot of further articulations, mostly finer differentiations of the Baroque articulations. In addition, multiple articulation instructions can be combined. A typical example is the addition of an accent over a somehow articulated note for additional dynamic emphasis.

Our approach to articulation in synthetic performances shall provide this flexibility and extensibility. This would, for instance, facilitate an analysis-by-synthesis approach to expressive articulation and further customization.

All implementations were done in a MIDI-based music engine framework [2]. It loads the raw MIDI data and several performance styles in XML format which explicitly describe how to render expressive MIDI sequences. Such a performance style includes information on all performative aspects such as tempo, rubato (self-compensating micro-deviations in timing), asynchrony, ‘human’ imprecision, dynamics, metrical emphasis, and, of course, articulation. It can be created, for instance, by a performance generation system and/or manually edited. Regarding the aspect of articulation, the following formalisms have been developed and implemented.

4.1 Concept

The basic idea is to formally separate the definition of articulations from their application to the concrete musical context. Therefore, the formalisms *articulation style* and *articulation map* are introduced.

An articulation style is a pool of articulation definitions. One such definition describes the manipulations which the articulation makes to an input note. The developer can freely edit them and create any, even new, articulations. Several styles with possibly differing definitions can be defined.

An articulation map is a sequence of instructions to articulate a concrete musical context, in our implementation a raw MIDI sequence. Only high-level descriptors are used which act as lookup references to the definitions in an articulation style. Articulation maps can be manually edited or output of a performance generation system. For playback, the instructions are then rendered into an expressive MIDI sequence.

4.2 Articulation Style

An articulation style S_s $(s = 0...t)$ is an element of a set of styles $\mathcal{S} = \{S_0, ..., S_t\}$. It is a set of articulation instructions.

$$S_s = \{I_0^s, ..., I_j^s\}$$

An articulation instruction defines the manipulations it applies to a raw note by a list of manipulators.

$$I_i^s = (M_0^{s,i}, ..., M_n^{s,i}) : i = 0...j, n \geq 0$$

One such manipulator is a triple which indicates mode and value of the manipulation, and the note attribute to be changed.

$$M_m^{s,i} = (mode_m^{s,i}, attribute_m^{s,i}, value_m^{s,i}) : m = 0...n$$

Possible attributes to change are the note's duration and velocity. Three manipulation modes are distinguished

$$attribute := \begin{cases} value & : \text{set mode} \\ attribute + value & : \text{add mode} \\ attribute \cdot value & : \text{percent mode} \end{cases}$$

Negative results are restricted in either case. The implementation further rounds the results to integers for proper performance in MIDI. If the velocity attribute is modified, the result is capped if greater than 127. While the set mode sets the attribute absolutely, the add and percent mode assume that the attribute is already set at the basic value (e.g., dynamics). Articulation quasi adds finer differentiations.

For the manipulation of duration values the implementation provides a millisecond version. Thereby, it allows to set durations not just in MIDI ticks but also in milliseconds. Corresponding timing conversions are described in [3].

In the implementation, the indices s (style index) and i (instruction index) were replaced by unique name strings. These descriptors are used in the articulation map as lookup references. They ease the manual editing of articulation maps as they allow to call a spade a spade. This is particularly necessary for sample-based MIDI playback. The *Vienna Instruments* sampler [21], for instance, provides specialized sample sets named 'staccato', 'legato', 'portamento', 'pizzicato' and so forth. These have to be triggered separately by designated controller messages. If an instruction with a known name occurs, our system automatically activates the respective sample set. The current vocabulary comprizes the terms 'portamento', 'legato', 'moltoLegato', 'legatissimo', 'nonlegato', 'portato', 'marcato', 'tenuto', 'staccato', 'staccatissimo', 'spiccato', and 'pizzicato'.

Nonetheless, the developer is free to define and name any articulation. Only the neutral articulation plays a special role. If an articulation style defines a neutral articulation, it is applied to all notes except for those with individual instructions in the articulation map.

4.3 Articulation Map

The articulation map is a sequentially ordered list with two types of elements, *style switches* and *articulators*. A style switch is a tuple

$$switch = (d, s) : d \geq 0, S_s \in \mathcal{S}$$

with the tempo-independent date d (e.g., in MIDI ticks) from when on articulation style S_s acts as the underlying style, quasi as the lookup style. Its range is terminated by the date of the next style switch. The first element in an articulation map has to be a style switch.

The other elements in the map are articulators. This is a tuple

$$articulator = (note, (i_0, ..., i_k)) : I_{i_{0...k}}^s \in S_s, k \geq 0$$

that indicates the note *note* to be articulated, and the articulation instructions $I_{i_{0...k}}^s$ therefore. The instructions are successively applied to the note. In this way, instruction combinations are possible, like *tenuto* and accent, or even double accent (one accent may raise the velocity by a certain amount, double accent does it twice then).

But the note to be articulated must be located in the MIDI sequence. All necessary information therefore are given by the *note* term. It is a list of properties (date, pitch, duration, MIDI channel and port). Most of them are optional, only the date (in MIDI ticks) is always required. If the given information allow no clear discrimination of several notes, all contemplable notes are articulated.

4.4 Discussion

The described system allows to model a broad variety of articulations. All basic articulations and a big spectrum of nuances are possible. The quality of the sounding results depends, of course, also largely on the underlying sound technology (quality of samples or synthesized sound). Nonetheless, the expressive intentions of the articulation are still discernible, even with low-quality sounds.

The system implements articulation manipulations in the loudness and duration domain. Even the timbre domain can be handled to a certain extent through specialized sampler control. Serious boundaries exist with regard to envelope and pitch/intonation. The latter can be added easily: The manipulators' *attribute* domaine can be extended by *pitch*. The respective changes can be implemented by pitch wheel controller messages.

The flexible manipulation of envelope characteristics, by contrast, necessitates more access to the sound generation process. Special playing techniques, like *con sordino*/muting the instrument, bowing with bridge proximity, playing and singing into the mouthpiece at the same time etc. necessitate advanced synthesis methods and full synthesizer control.

Up to now, articulations are rendered into MIDI sequences without any variance. A human performer is not able to reproduce an articulation that exactly, though. By a certain random variation further liveliness can be introduced. But which amount of variance would be reasonable, anyway? It can be more for layman musicians and less for professionals. Concrete values are still unknown and await detailed analysis and evaluation.

Similarly, our implementation uncovered a further very fundamental question. Is articulation additive? A *staccato* articulation may set the tone length to 170ms. Adding a *marcato* articulation may shorten the tone length by further twenty percent and raise its velocity to the next dynamic level (e.g., from *mf* to *f*). Is this adequate? More meaningful combinations, like *staccato+tenuto*, *staccato+legato* or *tenuto+legato* are well known from music notation. On the other hand, combinations of instructions which affect the tone duration might rather averaged than added. A short articulation combined with a long may result in a medium duration (e.g., $staccato + tenuto \approx portato$). But how are both articulations weighted? The generative nature of our articulation approach inspires further investigation into such effects.

5. CONCLUSION

Articulation, if not reduced to a mere tone duration feature, offers a big potential for synthetic music performances. When human performers change articulation, they alter tone features like loudness, envelope, duration, and, as presumed, timbre and pitch. Our analyses of late Baroque articulation showed that these variations do not derive from other performance features like timing and dynamics.

Although these features are systematically distinguished they are perceived as fused. As an example, we demonstrated the pseudo-crescendo by increasing duration, which is already known in theory [1] and practise. These fusion effects are worth further investigations.

Music includes a great amount of common practices, but these can disappear every time as music progresses. Research into music and its original performance accordingly should consider both structure and origin. Synthetic performance systems can contribute to this rediscovery.

This paper further described the implementation of articulation features as part of such a performance system. The implementation allows to flexibly define any articulation styles and apply them to a given raw MIDI sequence. A musicologically interesting part is the chance to easily render one and the same raw sequence in different styles, adapt the styles, and explore the effects on the performance.

Of course, were articulation added solely, no performance would sound expressive. Articulation rather supplements music expression as timing and dynamics do as well. Hence synthetic and expressive music cannot sound human-like until these three are combined.

Acknowledgement

We like to express thanks to all musicians for their participation in the recordings and for the inspiring dialogs.

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