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Measurements and models of musical articulation

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Contents

Abstract

In organ playing the only means for sudden changes in expression is altering of the tone onsets and offsets. While interonset intervals (IOIs) have been studied extensively in several instruments, the distribution of offset timings is largely unknown. In order to study phrasing, it is sufficient to measure the onsets. However, articulation measurements require the extraction of offsets as well.

In this study, the tone onsets and offsets were measured in four monophonic Bach organ fugue openings (BWV 537, 542, 564, 578), each of which was played by three or four organists sampled from commercially available recordings. The articulations, IOIs, and relative IOIs of all tones were calculated, as well as a number of inter- and intra-personal correlation coefficients. The articulation for each tone was taken to be the ratio between the tone duration and the IOI. The relative IOI is a measure of the local tempo deviation. The articulatory strategies were charted in all performances using an explorative (not hypothesis-driven) approach.

The mean articulation was found to be 0.84, with an average standard deviation of 0.18. The mean correlation coefficient between performers' articulations in the same piece was 0.46, which is almost as high as for the relative IOI (0.52). The mean correlation between articulation and relative IOI was –0.32, meaning that in the studied material lengthening of relative IOI typically coincides with shorter (more *staccato*-like) articulation. It is notable that for relative IOI's below 0.9 there were no tones with articulation below 0.7. For relative IOI's above 1.15, on the other hand, there were no tones with articulation above 0.7.

Some performances are articulated binary, i.e. long or short but not in between. Other articulation strategies enhance the phrasing or the metrical structure (with more staccato on weak beats).

In conclusion, musical articulation seems to be no more random than for example phrasing, but it is more complex, because performers can use mutually exclusive articulation strategies yielding non-identical results. This fact makes evaluation of articulation models more difficult. Still, it should be possible to model articulation with at least moderate success. Two types of models are briefly outlined.

Sammanfattning

I orgelspel är de enda möjligheterna att snabbt förändra uttrycket att rucka på tonernas starttider (onsets) och sluttider (offsets). Intervallen mellan tonernas starttider (IOI, inter-onset interval) har studerats flitigt hos flera instrument, medan sluttidernas fördelning till stora delar är okänd. För att studera frasering är det tillräckligt att mäta starttiderna. För att mäta artikulationen måste man dock utvinna även sluttiderna.

I denna studie mättes tonernas start- och sluttider i fyra enstämmiga Bach-fugaöppningar (BWV 537, 542, 564, 578), var och en spelad av tre eller fyra organister i kommersiellt tillgängliga inspelningar. Artikulation, IOI och relativ IOI beräknades för alla toner, liksom ett antal korrelationskoefficienter inom och mellan organisterna. Med artikulationen för en ton avses förhållandet mellan tonens faktiskt uthållna längd och IOI. Relativ IOI är

ett mått på den lokala tempoavvikelsen. Artikulationsstrategierna kartlades i alla inspelningar enligt en explorativ (ej hypotesprövande) ansats.

Medelartikulationen befanns vara 0,84, med en genomsnittlig standardavvikelse på 0,18. Medelkorrelationen mellan olika organisters artikulation i samma stycke var 0,46, vilket är nästan lika högt som för relativ IOI (0,52). Medelkorrelationen mellan artikulation och relativ IOI var –0,32, vilket innebär att större relativ IOI i det studerade materialet typiskt sammanföll med kortare (mer *staccato*-artad) artikulation. Noterbart är att inga toner med relativ IOI lägre än 0,9 uppvisade artikulation lägre än 0,7. Toner med relativ IOI över 1,15 hade å andra sidan aldrig artikulation över 0,7.

Vissa tolkningar uppvisar binär artikulation, dvs. varje ton är antingen lång eller kort men inte mittemellan. Andra artikulationsstrategier framhäver fraseringen eller den metriska strukturen (med mer staccato på svaga taktdelar).

Musikalisk artikulation förefaller sammantaget inte vara mer slumpmässig än frasering, men den är mer komplex, eftersom musiker kan använda olika, ömsesidigt uteslutande artikulationsstrategier som inte ger likadana resultat. Detta faktum försvårar utvärdering av artikulationsmodeller. Det bör ändå vara möjligt att modellera artikulation åtminstone måttligt framgångsrikt. Två modelltyper presenteras skissartat.

Introduction

What is "musical articulation"?

In a dissertation on the interpretation of J. S. Bach's organ works, written by the Finnish organist and musicologist Enzio Forsblom, one reads: "By articulation we here refer to the tying or separation of the tones, through which the expression of the melodic line can be affected. In opposition to this, the phrasing slurs unite the tones belonging together in a phrase and mark the phrases off from one another" (Forsblom 1957, p. 54).[1] This catches two important features of what is generally meant by "musical articulation".

First, articulation has to do with the *individual tone* and its relation to the neighbouring tones.[2] Thus, *staccato* and *legato* are said to be manifestations of articulation. Secondly, Forsblom touches upon the ability of articulation to affect the musical expression. This is hardly surprising. Musical interpretation does indeed convey emotions; this has surely been known for a long time, though it has been scientifically scrutinized only recently; for a comprehensive review, see Juslin (2001). For example, when performers are asked to play a piece first in a neutral way and then in a specified expressive way (e.g. "happy" or "sad"), the articulation is changed, as are many other factors. "Articulation strongly affects motional and emotional character", Friberg & Battel (2002, p. 209) assure us, echoing Keller, who already three quarters of a century earlier told his readers that articulation is "for the melody the most important means of expression" (Keller 1925, p. 6).[3]

The German musicologist Hermann Keller is an important person in this area. In 1925 he published *Die musikalische Artikulation insbesondere bei Joh. Seb. Bach* ("Musical Articulation, Especially in Joh. Seb. Bach", no English translation available). Thirty years later, he completely rewrote the book and published it with the title *Phrasierung und Artikulation* (*Phrasing and Articulation*, English translation 1965). As for the distinction between articulation and phrasing – sometimes used synonymously by musicians and musicologists – Keller was clear-cut: "[T]he words 'phrasing' and 'articulation' have basically different meanings: *phrasing* is much like the subdivision of thought; its function is to link together subdivisions of musical thought (phrases) and to set them off from one another; it thus has the same function as punctuation marks in language. (…) The function of musical *articulation*, on the other hand, is the binding together or the separation of the individual notes; it leaves the intellectual content of a melody line inviolable, but it determines its expression" (Keller 1965, p. 4).

In musicology the term "articulation" is sometimes attributed a very wide scope. In a much-read book on style analysis (LaRue 1992), for example, every change, from one symphony movement to the next, as well as from one tone to the next, is said to constitute "articulation". However, articulation is normally associated with small dimensions, whereas phrasing acts on a larger scale (though admittedly not as large as to include complete symphony movements).

Let us not plunge too deeply into matters of definition. Nonetheless, it is important to recognize that there is a variety of strategies for making adjacent tones belong together or

[1] My translation. Swedish original: "Med artikulation avses här sammanbindandet eller åtskiljandet av tonerna, varigenom den melodiska linjens uttryck kan påverkas. I motsats härtill förenar fraseringsbågarna de toner som hör samman i en fras och avgränsar fraserna från varandra".

[2] Similar opinions can be found in, e.g., Ferguson (1975), p. 53, and Chew (2001), p. 86.

[3] My translation. A more elaborate German original reads: "[I]n der zweiten [Bedeutung] hat sie [=die Artikulation] einen manchmal entscheidenden Einfluß auf den Zusammenschluß der Motive und wird dann für die Melodie das wichtigste Ausdrucksmittel überhaupt".

for making them seem separated. Tones can be played longer or shorter than their nominal duration. Furthermore, tones can be played with different sound levels, or with different vibrato, or with different tone attacks, etc. Adjustment of the amount of rest between the tones – the most obvious articulation strategy – is far from the only possibility.

In this work I will only deal with methods involving the timing of the tones. There are two such methods. The first is to alter the relative length of the rest, i.e. what is normally called *legato* vs. *staccato*. If one note ends exactly when the following note starts, the articulation ratio (or simply articulation[4]) is 1 (one). If one note lasts for only half the time between its onset and the onset of the next tone, the articulation is 0.5. In other words the articulation for tone *n* is $(\text{offset}_n - \text{onset}_n)/\text{IOI}_n$, where IOI is the *interonset interval* (see e.g. Friberg & Battel 2002), defined as the time interval between the onset of a given tone and the onset of the immediately following tone, i.e. $\text{IOI}_n = \text{onset}_{n+1} - \text{onset}_n$.[5]

The second method is to play the tones (or, more to the point, their IOI's) longer or shorter than their nominal duration. In other words the tempo is altered locally. This can be expressed in terms of relative IOI. A relative IOI of 1 (one) means that the duration of the tone is exactly what is to be expected from the nominal (notated) length given the mean tempo of the piece. For example, if a piece is performed at the mean tempo 120 quarter-notes per minute, we would expect an eighth-note to last for 0.25 s. A certain eighth-note with a duration of 0.30 s then has the relative IOI 0.30/0.25 = 1.2.

Earlier studies

In keyboard instruments it makes sense to say that "[a]rticulation – at least in the sense of staccato versus legato – may be defined mathematically as the ratio of tone duration to IOI" (Friberg & Battel 2002, p. 209). In keyboard instruments the tone length is by far the most important articulation factor.[6] But in other instruments this is not necessarily true. For example, in most wind and string instruments it is possible to alter the dynamics of individual tones, e.g. to make a *crescendo* on a single tone or to play a *fortepiano*. Such features surely contribute to articulation.

The musical polyphony, the entanglement of different voices, may also have a determining influence on articulation strategies. Howard Ferguson writes on articulation in keyboard instruments: "This 'characterization' of themes is one of the most important functions of articulation in the performance of early music, for it brings out their inherent life and enables the most involved contrapuntal textures to remain transparent. Another of its functions is to define the smaller units out of which passage-work is built" (Ferguson 1975, p. 57). This would for example suggest that a simple melody is articulated in one way if it is performed alone, and in another way if it is accompanied by other instruments. I am not sure that this is true, but it could be. Ferguson seems not to have investigated the question empirically.

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[4] From now on I will call this particular articulation stategy *articulation*, for simplicity. This is the strategy I will examine most carefully in this study. However, I will also discuss other articulatory strategies, and in doing so "articulation" of course will not refer to the particular strategy of altering the intervening rest, but to the much broader concept. The context will determine the meaning of the word in each case.

[5] It should be noted, incidentally, that the term "IOI" is well-established from earlier studies, whereas "articulation" in the specified sense "(offset – onset)/IOI" perhaps is not. Some researchers, e.g. Bresin & Battel (2000), use the terms "key overlap time" (KOT) and "key detached time" (KDT) in discussing legato and staccato in piano playing. The word "articulation" covers them both, being also applicable in other musical instruments.

[6] One could even argue that it is the *only* factor, but this is not true for all keyboard instruments. For example, in a pianoforte a sudden change of dynamics from one note to the other will make the tones appear separated even though the tone lengths are unchanged. The dynamics of individual tones thus contribute to articulation.

Simon Bolzinger (1995) studied the influence of different acoustical qualities of performance venues on piano playing. He concluded firstly that the acoustic feedback clearly influenced the playing intensity, so that "in most cases, a dull concert hall will require a greater physical effort from the interpreter" (p. 136).[7] Secondly, however, even though all interpreters reacted to changes in the acoustic feedback, the reactions were very diverse, depending on the interpreter, the style of the music and its technical characteristics, and even on the general situation. This diverse conclusion, abounding with reservations, is typical of the subject.[8] Although not investigated by Bolzinger, we should also remember that instruments change over time. An appropriate *Hammerklavier* articulation might not be suitable for a *grand piano* performance, not even for the same piece of music.

Alf Gabrielsson (1987) studied the timings in five performances of the opening Andante theme of Mozart's A major piano sonata, K. 331. He could demonstrate that most pianists showed similarities in tempo deviations. On articulation, Gabrielsson writes that "[a]lmost all the present performances are of the legato type" (p. 99). He discusses some exceptions to this observation, but there is no evidence that he actually measured the tone offsets.

Bruno H. Repp (1992) made a very large study of "temporal commonalities and differences" in piano playing. Repp measured the IOI's in no less than 28 recorded performances of Schumann's "Träumerei". His focus is on the behaviours such as *ritardandi* of structures called "melodic gestures" (two to seven notes long). Repp's paper contains many interesting observations. Again, it has nothing to report on articulation, since only the tone onsets were measured. The introductory part (p. 2546–2548) gives a valuable overview of earlier research.

In three subsequent papers, Repp specifically studied legato and staccato articulation in the piano (Repp 1995, 1997, 1998). However, the data material for these works were scales, arpeggios, and simple sequences, not "real" music as in the 1992 study. In all three papers the pianists were explicitely asked to play legato or staccato. Repp's findings were, for example: KOTs (key overlap times) for successive tones judged to be optimally legato were greater for high than for low tones (1995, 1997); note durations increased significantly as tempo decreased in both perception and production of staccato (1998). As indicated by the article titles, one of Repp's main concerns has been the relationship between perception and production of different articulations. He claims, e.g., that produced staccato is not necessarily percepted as staccato (1998).

One interesting study on piano playing was made by Giovanni Umberto Battel and Riccardo Fimbianti (1998). They studied the first 16 bars of the Andante movement of Mozart's G Major Sonata, K. 545. Five near-professional pianists played the piece nine times each. First they were asked to play it in an "optimal" (preferred) way, then in eight ways characterized by four pairs of expressive adjectives (bright vs. dark, light vs. heavy, hard vs. soft, and passionate vs. flat). The researchers performed several statistical tests relating the tone timings to the different adjectives ("intentions"). As for the articulation, they stated: "A close survey proves that the staccato/legato degree in each version depends on [harmonic] tension. Particularly, the DRO average of all performance notes depends on the expressive intention while, for each note, local value depends directly on the harmonic

[7] My translation. Original: "[D]ans la plupart de cas, une salle de concert plus sourde demandera un effort physique plus grande à l'interprète (…)".

[8] This is how Bolzinger puts it: "Cette faculté d'adaptation rétroactive, qui est donc commune à tous les interprètes, est nuancée toutefois par une grande diversité de réactions selon le contexte, puisque l'examen d'un échantillon de 37 enregistrements nous a amené à constater plusieurs attitudes différentes de l'interprète, voire opposées. Force est donc de constater la disparité des conséquences que peut avoir une modification de l'environnement sur l'exécution au piano, celles-ci dépendant a priori de l'interprète, du style et des caractéristiques techniques de la musique interprétée, et du contexte même en général" (ibid.).

structure. The performer increases the slur degree when the harmonic tension increases in each different intention, no matter the global value" (p. 69f). The DRO is explained to be "the ratio between the note value (key on/off) and the IOI" (p. 69), which appears to be identical to articulation in the present work.[9] In other words, Battel and Fimbianti claim that the average articulation is affected by the overall intention, but also that the individual values are dependent on the harmonic tension of each note. We are told that the tension for each note was calculated according to Lerdahl (1996). This result sounds very interesting, but since no details are given it is hard to assess the quality of the finding.

Battel and Roberto Bresin (2000) used the same material for further analysis. They concentrated more on articulation matters. They found that legato was played with a key overlap ratio which depended on the IOI.

When both onsets and offsets have been measured, as in some of the above studies, the material has been either scales and arpeggios or music where the composer has already added some phrasing and articulatory marks. The comprehensive reviews by Alf Gabrielsson (1999, 2003) confirm this picture; in studies of performance timing only the onsets seem to have been extracted in most cases.

Aim

The present study aims at a rough description of the articulation in one-part melodies played on the organ. I will report some basic findings. In particular I will investigate the following questions: What is "normal" articulation in one-part music lacking notated articulation marks, i.e. what is its mean and standard deviation?[10] How large differences are there between performers in the same piece? Is there any detectable relationship between articulation and IOI? Between articulation and relative IOI? If so, how could these be explained?

It seems that no one has investigated these questions before, at least not in a quantitative manner. There are some studies on how to play a predetermined articulation type, as indicated in the preceding section. For example, Bresin & Battel (2000) reports that a typical *staccato* in the pianoforte has an articulation ratio of approximately 0.4 (independent of absolute IOI). Repp (1995) reports that a legato in the piano has an articulation ratio of about 1.2.[11] However, there are no reports on the articulation of music without notated articulation marks. I will also devote some space to finding out whether specific articulation strategies are present in the pieces analysed. Some of the results have been summarised in Jerkert (2003).

Apart from exhibiting general articulatory observations, I will also investigate whether the obtained data conforms to the punctuation rule in the Director Musices (DM) program developed at KTH-TMH. DM inserts commas (micropauses) at places jugded suitable according to rules (Friberg et al. 2003). The rules utilised here only take melodic features into account. Since my material is wholly monophonic, a comparison with the DM results is appropriate.

The reason for analysing organ recordings rather than, say, violin recordings is that the articulation is straight-forward in the organ; it is only a matter of measuring the onset and offset of each tone. Furthermore, the organ tone is steady, being (very nearly) equally loud from onset to offset. There are some possibly complicating factors in that there is no standard organ. For example, organs might be mechanical or electro-pneumatic. Different

[9] This is confusing, since DRO in other papers on music performance stands for the *pause* duration, not the tone duration.

[10] Here I of course use the word "articulation" in the specific sense described earlier, i.e. the relation between the tone length and the IOI.

[11] Estimated by me from Repp's Figure 5, p. 3871.

organs do not respond in the same way to a given touch. These things have been ignored in this work. The rationale for this is the assumption that a skilful organist can produce an intended articulation on almost any organ (or at least on the organs of the analysed recordings).

Method

The material in this study is four Bach fugue openings for the organ. Some of Bach's fugue themes are rhythmically very monotonous (e.g. the fugue of the famous BWV 565) and so have not been considered. The material is from BWV 537, BWV 542, BWV 564, and BWV 578. By "opening" I mean from the beginning of the fugue (*dux*) to the entrance of the second voice (*comes*) or even shorter; the material is thus monophonic. Scores of the fugue themes are presented in Figure 1. These scores were redrawn from Keller (1925). There are notated pauses in one of the themes (BWV 564). In this fugue, notes immediately preceding pauses have been excluded from analysis. This is necessary because it is impossible to calculate their tempo deviations, and hence their relative IOI.

Figure 1: The four analysed fugue openings. From the top and down: BWV 537, BWV 542, BWV 564, BWV 578.

Each piece is played by three or four organists that were sampled from commercially available recordings, see Table 1 for details.

The onset and offset of each tone were estimated through spectrogram inspections. The programs WaveSurfer 1.4.5 (Sjölander & Beskow 2002) and Soundswell 4.0 (Hitech Development 2002) were used to supply spectrograms. Because of the very reverberant (and very different) recording conditions it was not possible to use an automatic procedure to establish the onset and offset timings, e.g. by defining them as the moment when the sound level exceeds or falls below a fixed number. The extraction of timings has thus been made manually, through ocular inspection combined with repeated playbacks.

For each performance the onset/offset timings were input to Matlab files calculating the articulation of each tone, the relative IOI and some statistical parameters. These Matlab files are not particularly advanced. Nevertheless, for the reader's reference the most important ones are reproduced in the Appendix.

As for the comparison between DM punctuation and measured articulation, the following method was adopted. In order to get for each piece a DM articulation for comparison with the real performers' values, tones immediately preceding a comma was assigned the articulation 0.5, while all other tones were assigned the articulation 0.8 (indicating that a comma is bound to make the articulation shorter). These articulation profiles were then matched against the real ones by calculating the correlation coefficients. Figure 2 shows the punctuation places according to DM.

BWV	Performer	Recording	Year
537	Hans Fagius	BIS 397/398	Ca 1988
537	Peter Hurford	Decca 443485-2	1979
537	Wolfgang Rübsam	Naxos 8553150	1988
542	Helmuth Rilling	Denon 38C37-7039	1974
542	Peter Hurford	Decca 443485-2	1978
542	Ton Koopman	Hänssler 98182	1986
542	Hans Fagius	BIS 308/309	Ca 1985
564	Peter Hurford	Decca 443485-2	1979
564	Ton Koopman	Archiv 410999-2	1983
564	Wolfgang Rübsam	Naxos 8550901	1993
564	Hans Fagius	BIS 343/344	1986
578	Helmuth Rilling	Denon 38C37-7039	1974
578	Wolfgang Rübsam	Naxos 8553135	1995
578	Hans Fagius	BIS 439/440	1989

Table 1. The recordings used for analysis.

Figure 2. Commas inserted according to Director Musices punctuation rule. From the top and down: BWV 537, BWV 542, BWV 564, BWV 578.

A note on models and assumptions

Different interpreters do not play a given piece identically, although similarities can be found. So there must be some random factors in articulation, at least in any model. It is important here to distinguish between reality and any model. In my opinion, there must be certain differences between different interpreters, no matter how tiny and insignificant, which have to be viewed as random differences. Even if an interpreter was explicitly asked to copy another performance, he would not succeed completely. The timings would not be exactly identical, due to the imperfection of the human neural system. Neural signaling, though impressive in many respects, has not an unlimited temporal exactness. There is some "thermal noise" in the system. For this reason, if for no other, random deviations have to be introduced in any model. However, this random factor operates on the smallest time-scale only; it affects the timing of single tones.[12] It should not affect the

[12] More on "random noise" is found in Juslin et al. (2002), where a distinction is made between small-scale randomness which is due to motor delay variance and random variations due to timekeeper variance. The latter variations can act on larger scales, e.g. in temporal drift.

typical phrase arc characteristics, like the slight *ritardando* at the end of phrases. The shaping of phrases is not likely to be random at all, though it may well be unconscious. In between these extremes – the exact timings of single tones and the formation of phrase arcs – we find what might be called *patterns*. Patterns concern the articulation of tone groups, possibly recurrent ones. For example, let us assume that I analyse a piece with this passage appearing in the printed notes,  , finding that one performer articulates like this: . That is what I would call a pattern. I cannot be sure that this articulation behaviour is "real", that is intended. On the other hand, I refrain from calling it random, because detaching the last note in each group seems musically resonable to me, given the leaps from the third to the fourth notes.

This is the point I want to make: For single tones, any result – expected or not – could be attributed to "chance" or "random fluctuations". For large scale findings such explanations are very unlikely. For the patterns, the question is open, unless you find the same patterns in very many cases. But my material is too little for this to happen. This – the limited amount of data – is the main weakness of the present work. That is why the question of intentionally or randomly caused patterns is delicate.

With this in mind, let us now turn to the results.

General results

Tempos

Table 2 shows the tempos chosen by the organists in all the performances.

BWV	Performer	Tempo (BPM)
537	Fagius	𝅗𝅥 = 61
537	Hurford	𝅗𝅥 = 73
537	Rübsam	𝅗𝅥 = 58
542	Rilling	♩ = 65
542	Hurford	♩ = 79
542	Koopman	♩ = 89
542	Fagius	♩ = 77
564	Hurford	♩. = 65
564	Koopman	♩. = 66
564	Rübsam	♩. = 54
564	Fagius	♩. = 54
578	Rilling	♩ = 62
578	Rübsam	♩ = 66
578	Fagius	♩ = 69

Table 2. Tempos in beats per minute.

Overall articulation

The mean articulation, for all pieces and all performances, was 0.84, with an average standard deviation of about 0.18. The results for each performance are presented in Table 3. As can be seen, there are some differences between pieces, which is quite expected because different pieces seem to invite the performers to articulate differently. However, the differences are small. The highest value including one standard deviation (0.98 ± 0.13) overlaps with the lowest value including one standard deviation (0.65 ± 0.23).

BWV	Performer	Mean art. ± SD
537	Fagius	0.93 ± 0.13
537	Hurford	0.89 ± 0.18
537	Rübsam	0.90 ± 0.13
542	Rilling	0.93 ± 0.23
542	Hurford	0.96 ± 0.15
542	Koopman	0.70 ± 0.21
542	Fagius	0.83 ± 0.14
564	Hurford	0.66 ± 0.27
564	Koopman	0.65 ± 0.23
564	Rübsam	0.86 ± 0.18
564	Fagius	0.73 ± 0.23
578	Rilling	0.98 ± 0.13
578	Rübsam	0.88 ± 0.16
578	Fagius	0.91 ± 0.11
Overall mean		0.84 ± 0.18

Table 3. Mean articulations and standard deviations.

BWV	Pair of performers	Art. corr.	Piece mean
537	Fagius-Hurford	0.31	0.44
537	Fagius-Rübsam	0.70**	
537	Hurford-Rübsam	0.32	
542	Rilling-Hurford	–0.14	0.30
542	Rilling-Koopman	0.76***	
542	Rilling-Fagius	0.34	
542	Hurford-Koopman	–0.01	
542	Hurford-Fagius	0.22	
542	Koopman-Fagius	0.63***	
564	Hurford-Koopman	0.60**	0.73
564	Hurford-Rübsam	0.52**	
564	Hurford-Fagius	0.71***	
564	Koopman-Rübsam	0.83***	
564	Koopman-Fagius	0.82***	
564	Rübsam-Fagius	0.90***	
578	Rilling-Rübsam	0.18	0.27
578	Rilling-Fagius	0.22	
578	Rübsam-Fagius	0.40**	
Overall mean		0.46	

Table 4. Articulation correlations between all performer pairs. The stars indicate statistical significance: * means $p < 0.05$, ** means $p < 0.01$,

and *** means $p < 0.001$. Please note that the significance levels were not adjusted for multiple testing.

A rough measure of the articulation similarities between performers is the mean value of all pairwise correlations. For example, there are three performer combinations for BWV 537: Fagius-Hurford, Fagius-Rübsam, and Hurford-Rübsam. This mean value, for all four fugues (18 performer pairs), was 0.46. An approximate 95% confidence interval is 0.33-0.60. The full results are presented in Table 4. Great similarities are found in BWV 564, indicating common articulation strategies. This is further discussed under "Piece studies".

Articulation and IOI

The IOI (or, for clarity, absolute IOI) is the duration of the tone, including the following pause (if any) before the next tone. It is straightforward to perceive. Relative IOI, on the other hand, is cognitively much more complicated, since it reflects the deviation from a notated duration, the existence of which the listener must deduce from the relative values only. Let us therefore first investigate whether we can find any interesting correlation coefficients when comparing IOI and articulation values. Table 5 shows the correlations between articulation and absolute IOI for each performance.

BWV	Performer	Correlation
537	Fagius	–0.20
537	Hurford	0.19
537	Rübsam	–0.07
542	Rilling	–0.94***
542	Hurford	0.15
542	Koopman	–0.88***
542	Fagius	–0.44***
564	Hurford	–0.23
564	Koopman	–0.65***
564	Rübsam	–0.90***
564	Fagius	–0.75***
578	Rilling	–0.15
578	Rübsam	–0.31*
578	Fagius	–0.04

Table 5. Correlations between articulation and absolute IOI for all performances. The stars indicate statistical significance: * means $p < 0.05$, ** means $p < 0.01$, and *** means $p < 0.001$. Please note that the significance levels were not adjusted for multiple testing.

Most correlations are negative, but only a few of them are highly significant. The most significant *p* values are found in BWV 542 and BWV 564. The only non-significant contributions in these pieces are both played by Hurford. Obviously, for all other performers a negative correlation between articulation and IOI is preferred. Why BWV 542 and BWV 564? The reason might be that both themes consist entirely of only two notated note lengths, namely eighth-notes and sixteenth-notes. If the longer notes are generally given another articulation (here: shorter) than the short notes, the correlation can easily be very significant, because the notes are divided into two distinct groups along both the IOI and articulation dimensions.

All data are presented in Figure 3.

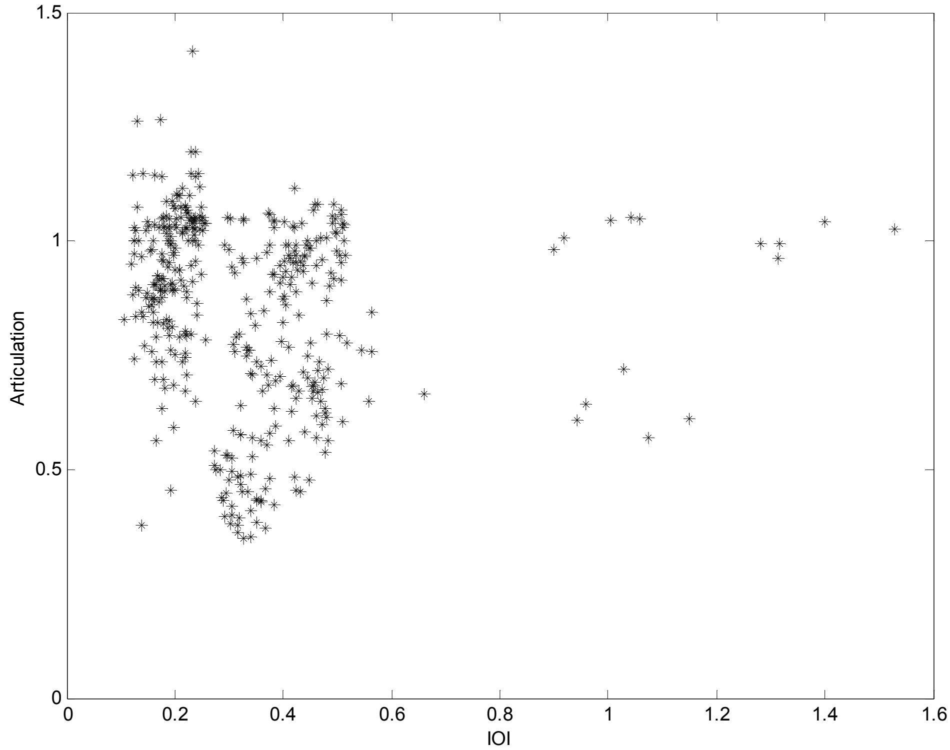


Figure 3. IOI vs. articulation for all data, i.e. all performances of all pieces. IOI is measured in seconds.

Articulation and relative IOI

Articulation and adjustment of relative IOI are the two temporal strategies for joining or separating adjacent tones. The relative IOI consistency, measured as the mean correlation between performers, was 0.52. An approximate 95% confidence interval is 0.42-0.61. No correlation was negative (out of 18 combinations). The value is somewhat higher than the mean correlation for articulation between performers.

BWV	Performer	Correlation	Piece mean
537	Fagius	–0.36	–0.16
537	Hurford	0.21	
537	Rübsam	–0.34	
542	Rilling	–0.02	–0.29
542	Hurford	–0.02	
542	Koopman	–0.61***	
542	Fagius	–0.53**	
564	Hurford	–0.08	–0.50
564	Koopman	–0.52**	
564	Rübsam	–0.74***	
564	Fagius	–0.66***	
578	Rilling	–0.04	–0.26
578	Rübsam	–0.47**	
578	Fagius	–0.26	
Overall mean		–0.32	

Table 6. Correlations between articulation and relative IOI for all performances. The stars indicate statistical significance: * means $p < 0.05$, ** means $p < 0.01$, and *** means $p < 0.001$. Please note that the significance levels were not adjusted for multiple testing.

Relative IOI deviations have been studied fairly extensively. To find a relationship between relative IOI and articulation would therefore be helpful, since it could provide a shortcut in simulations of realistic articulation in computer music. Should we expect such a relationship? A negative correlation might seem obvious: if a tone is given a fixed duration, then prolonging its IOI would mean adding time to the following rest, thereby reducing its articulation. This would mean that longer IOI's are more likely to be associated with shorter (more *staccato*-like) articulation. But *a priori*, one could as well argue that the opposite could be true: perhaps shorter tones must be articulated more clearly (i.e. more *staccato*) to be heard in their own right, whereas longer tones do not need such clarification. If so, longer IOI's are more likely to be associated with longer (more *legato*-like) articulation. Or maybe none of these alternatives is true.

In this study, the mean correlation between articulation and relative IOI for all performances was negative, –0.32. An approximate 95% confidence interval is –0.46 - –0.17). All correlations were negative except one (out of 14). The results are presented in Table 6.

Another way of handling this material is to look at the mean value for each performer. Table 7 shows the correlations from Table 6 averaged for each performer.

Performer (no. of performances)	**Mean correlation**
Fagius (4)	–0.45
Hurford (3)	0.04
Rübsam (3)	–0.52
Rilling (2)	–0.03
Koopman (2)	–0.56

Table 7. Mean value for correlations between articulation and relative IOI for all performers.

Table 7 is interesting information. Two organists, Hurford and Rilling, show correlations barely separated from zero. The other three show clearly negative correlations. Of course, this data set is too little to establish the calculated values as "typical" for these performers. But the set is sufficient for the assessment that there seems to be a variability in the articulation/relative IOI correlation between performers. Negative correlations are predominant, but there are performers with approximately zero correlations.

The whole material is presented in Figure 4. The correlation is, as mentioned, –0.31. Due to the large amount of data, p is very low: $p < 10^{-6}$.

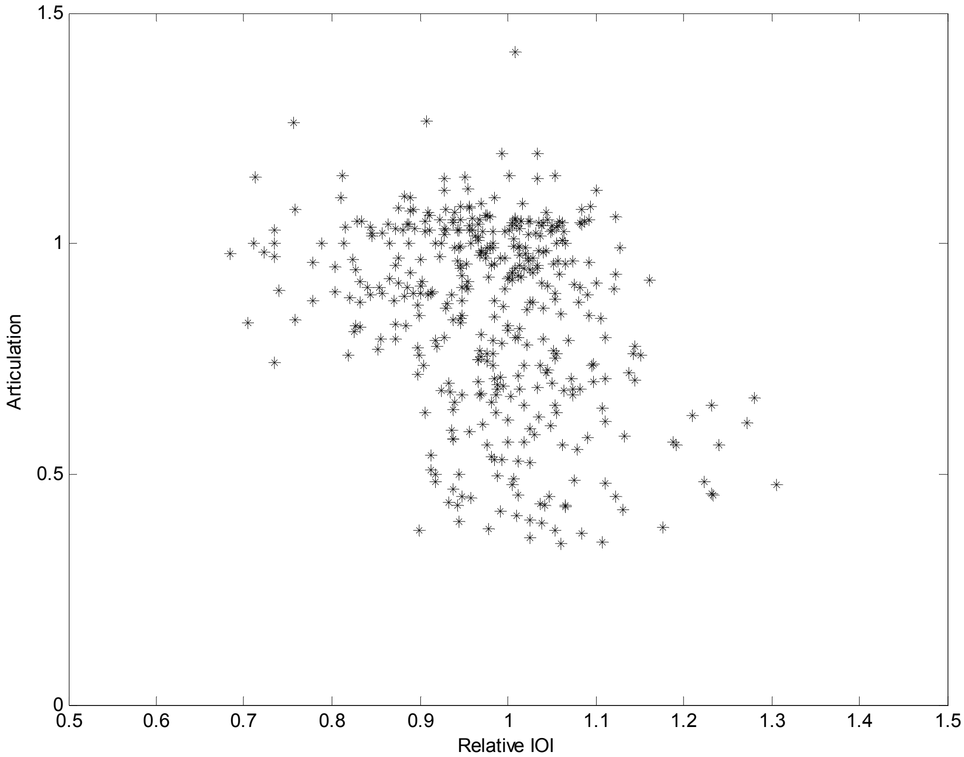


Figure 4. Relative IOI vs. articulation for all data, i.e. all performances of all pieces.

Although Figure 4 assembles data from different performers and different pieces, one thing is striking: There are no data in the lower left or upper right corners. For relative IOI's below 0.9 there are no tones with articulation below 0.7. For relative IOI's above 1.15, on the other hand, there are no tones with articulation above 0.7.

DM punctuation rule vs. measured articulation

BWV	Performer	Correlation performer vs. DM
537	Fagius	–0.23
537	Hurford	–0.33
537	Rübsam	–0.39
542	Rilling	0.57
542	Hurford	–0.04
542	Koopman	0.69
542	Fagius	0.56
564	Hurford	–0.34
564	Koopman	–0.50
564	Rübsam	–0.18
564	Fagius	–0.22
578	Rilling	0.23
578	Rübsam	–0.09
578	Fagius	0.26
Overall mean		0.00

Table 8. Correlation coefficients for DM punctuation vs. real performances.

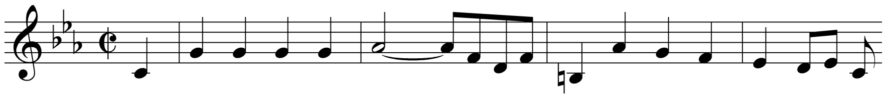
Table 8 shows all the correlation coefficients between real performance data and the 0.5/0.8 articulation assigned to simulate the DM punctuation rule (described above, under "Method").

The mean value is very discouraging indeed! Overall, there is absolutely no support for the idea that the DM punctuation rule, as implemented here, catches any important characteristic of monophonic organ playing. The reason for this failure will be meditated upon in the "Discussion" section. Some cases will be commented in the "Piece studies" section.

Piece studies

In this section I will chart the articulatory patterns in each piece, as revealed by the assembled data for articulation and relative IOI. The results will be presented under different subheadings within each piece, but there will always be a "Summary" subheading under which all the data will be presented graphically. It will often be helpful to keep an eye on this summary graph when reading the preceding paragraphs.

BWV 537



Fagius and Rübsam

Plotting Fagius' articulation vs. Rübsam's shows a fairly linear relationship (Figure 4). It is reasonable to say that Fagius uses a binary type of articulation, either short or long. As seen in Figure 5, in Fagius no tones have articulations between 0.8 and 0.9. For Rübsam the pattern is not equally clear. His articulation values are more evenly spread. However, adopting 0.8 as the boundary between short and long articulation for both performers, only two eighth-notes at the end of the theme are disputed, as shown in Figure 6.

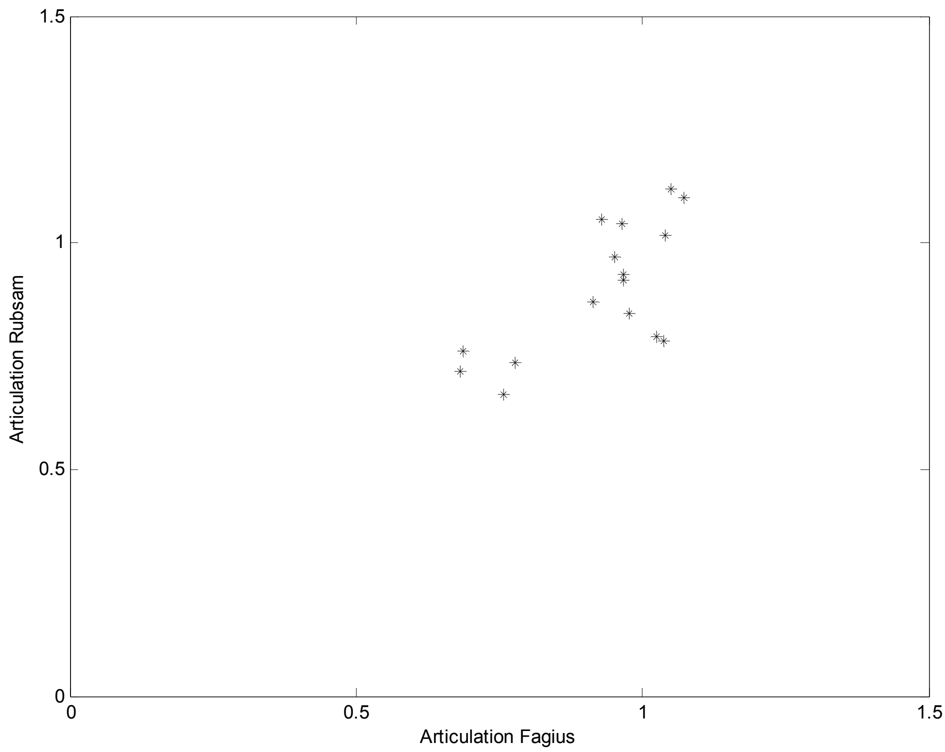


Figure 5. Articulation in BWV 537 for Fagius and Rübsam. The two outliers closest to the bottom right corner are the two disputed eighth-notes *D* and *E flat* at the end of the theme.

Figure 6. Articulation in BWV 537 for Fagius and Rübsam. Tones for which the articulation is less than 0.8 are marked staccato, other notes are marked portato. The two disputed tones are marked both ways.

Hurford's deviations

Hurford uses roughly the same articulation, but he is more extreme, reaching articulations below 0.6 on three occations. At the same time he plays with the most stable tempo of the three performers, his relative IOI never exceeding ±10% (see Figure 8, top). It seems resonable to say that Hurford compensates his moderate tempo deviations with more expressive articulation; but this can only be an intelligent guess given the small data sample. Figure 7 shows Hurford's articulation in musical notes.

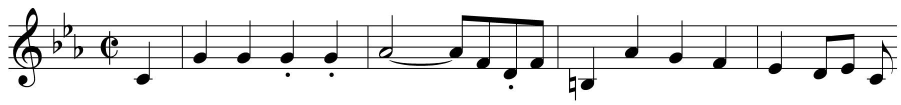


Figure 7. Hurford's articulation in BWV 537. Staccato dots indicate articulations of below 0.6. All other tones have articulations above 0.9.

The diminished seventh leap

A striking feature of the BWV 537 fugue is the diminished seventh leap from B natural up to A flat. What is interesting about this is that no performer marks the B natural off from the A flat by inserting a pause or comma. Nothing remarkable is found in the relative IOI or articulation graphs (Figure 8). This should be contrasted to the DM program, which inserts a comma at this point. The rule insertion is made on purely melodic grounds. The live performers may consider the B natural and A flat as belonging to the same diminished four-tone chord, thereby joining them articulatorily. Another possibility is an influence of the metrical structure; the B natural is on a strong beat, which seems to incite legato articulation (more on this topic below). It should be noted that the DM punctuation rule does not include any subrules concerned with metrical structure.

The upbeat

Fagius and Rübsam plays the upbeat staccato (Figure 6), while Hurford plays legato (Figure 7). As mentioned, Hurford is somewhat more extreme in his articulation, but I find no obvious reason for the upbeat discrepancy. Judging from the other BWV 537 data, one would not have been surprised by a staccatissimo upbeat in Hurford.

Summary

All three performers play the two or three last tones in the row of four identical G's staccato. Overall, the articulation strategies were fairly similar, Hurford being somewhat divergent. Figure 8 shows all articulatory data in BWV 537.

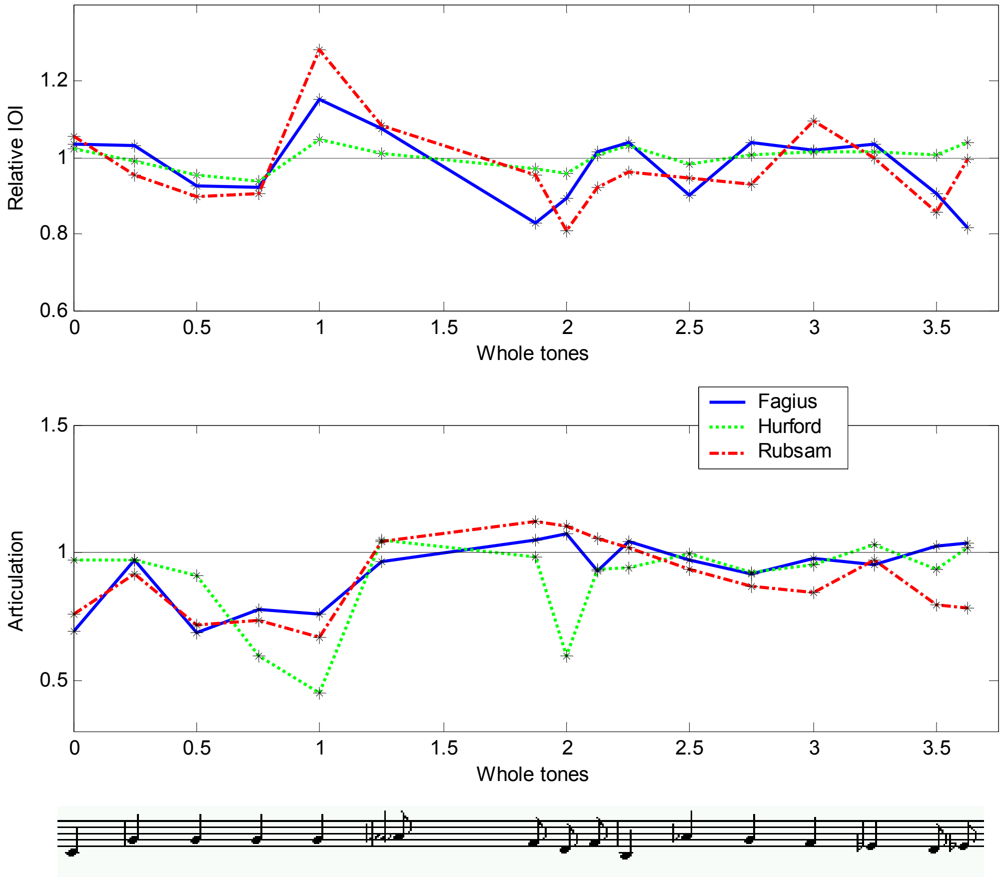
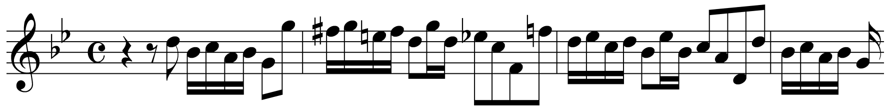


Figure 8: Relative IOI (top) and articulation (bottom) for all four performances of BWV 537. Musical notes are shown at the bottom for vertical orientation.

BWV 542



The great g minor Fantasia and Fugue BWV 542 is one of Bach's most well-known organ pieces. The fugue is quite fast, with only eighth-notes and sixteenth-notes intermingling.

Koopman and Rilling: Binary articulation

According to Table 3, in Koopman has a mean articulation of 0.70, whereas Rilling has 0.93. Still, their articulation profiles are very similar, as shown in Figure 9. They have both adopted a binary type of articulation; either short (for Koopman 0.37–0.57, for Rilling 0.57–0.75) or long (for Koopman 0.73–1.04, for Rilling 1.02–1.20). Since they have chosen the same type of articulation for all tones, with only one or two exceptions, the points in Figure 9 are gathered in two distinct groups.

What is the explanation of the striking similarity found in Koopman and Rilling? The answer is simple: All long notes (eighth-notes) are played short, while all short notes (sixteenth-notes) are played long; see Figure 10.

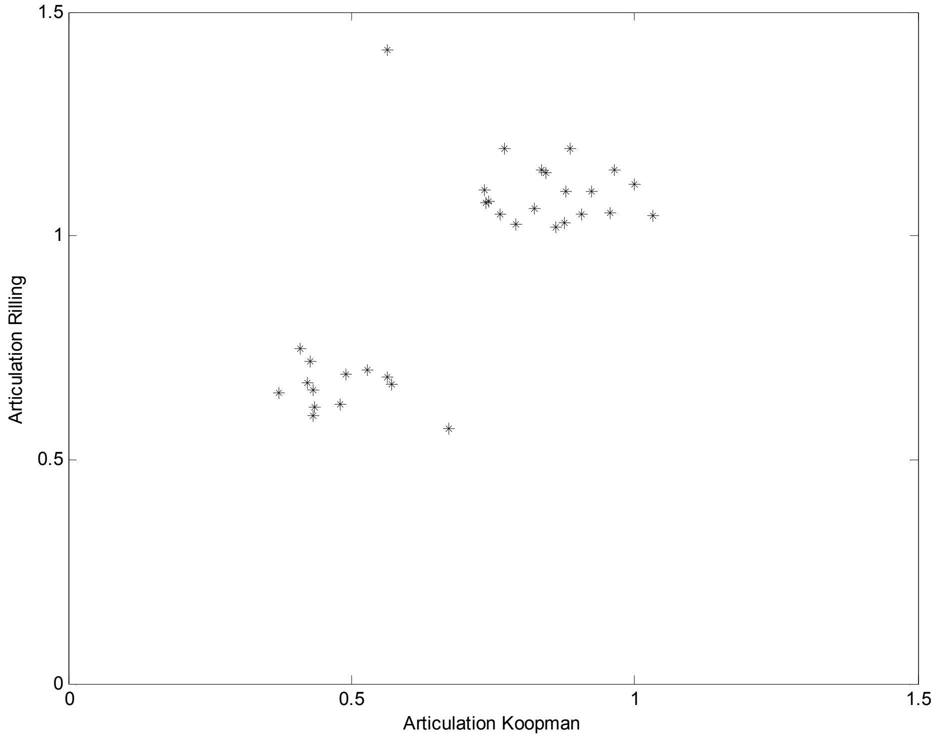


Figure 9. Articulation in BWV 542 for Koopman and Rilling. The binary character is clear in both performers, but it is most accentuated in Rilling.

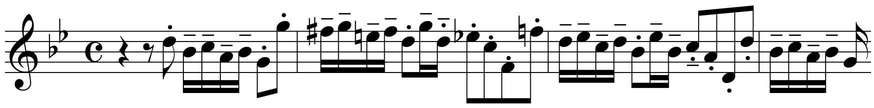


Figure 10. Articulation in BWV 542 for Koopman and Rilling. Staccato dots indicate articulations of 0.37–0.57 for Koopman, 0.57–0.75 for Rilling. Portato strokes indicate articulations of 0.73–1.04 for Koopman, 1.02–1.20 for Rilling.

Hurford: Less distinct patterns

Turning to Hurford, it is not as easy to find distinct articulation types. Almost all articulation ratios are between 0.86 and 1.15. Four notes have articulation values below 0.76. These four notes are marked with staccato dots in Figure 11. They are not randomly scattered but are the last two notes in a recurrent group of four. All other notes have articulation values of 0.86 or more.

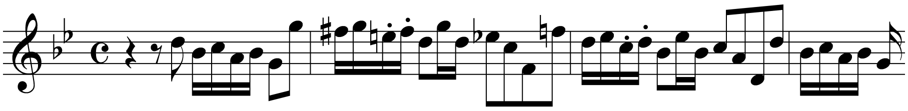


Figure 11. Articulation in BWV 542 for Hurford. Staccato dots indicate articulations of less than 0.76. All other notes have articulations of 0.86 or more.

Fagius: No obvious pattern

As can be seen in Figure 12, Fagius' articulation is in no way distinguished; for many notes it comes close to the average articulation of the other three organists. Still, it is hard to find patterns. In Figure 12 three different articulations have been indicated, but the boundaries between them are quite arbitrary. There is a tendency of shortening notes immediately preceding the beats, but this seems to be fully explained by corresponding lengthenings of the relative IOI's. In this way Fagius has emphasized the metrical structure, but he has not used any specific articulation strategy separable from simply adjusting the relative IOI's.

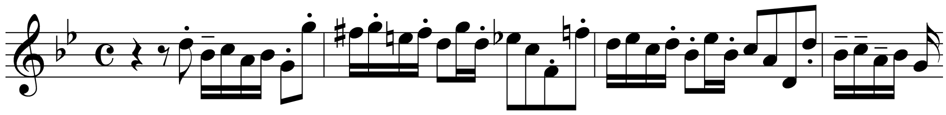


Figure 12. Articulation in BWV 542 for Fagius. Staccato dots indicate articulations of 0.56–0.79, portato strokes indicate articulations of 1.03–1.05, neither dots nor strokes indicate articulations of 0.81–0.98.

The upbeat

Three out of four performers played the upbeat detached. There is no relationship with the relative IOI's in this matter.

Summary

In conclusion, Koopman and Rilling adopted a simple and almost perfectly consistent strategy: long notes were played short and short notes were played long. Hurford played most notes quite long, but showed a tendency of shortening the last two sixteenth-notes in the groups of four sixteenth-notes (though he did it in only two out of four groups). This pattern – binding the first two notes and separating the last two when encountering groups of four short notes – is well-known in classical Western music, not only in the organ (see e.g. Keller 1965, pp. 95f, 107). Fagius, finally, exhibited no obvious articulation pattern. Figure 13 shows all articulatory data in BWV 542.

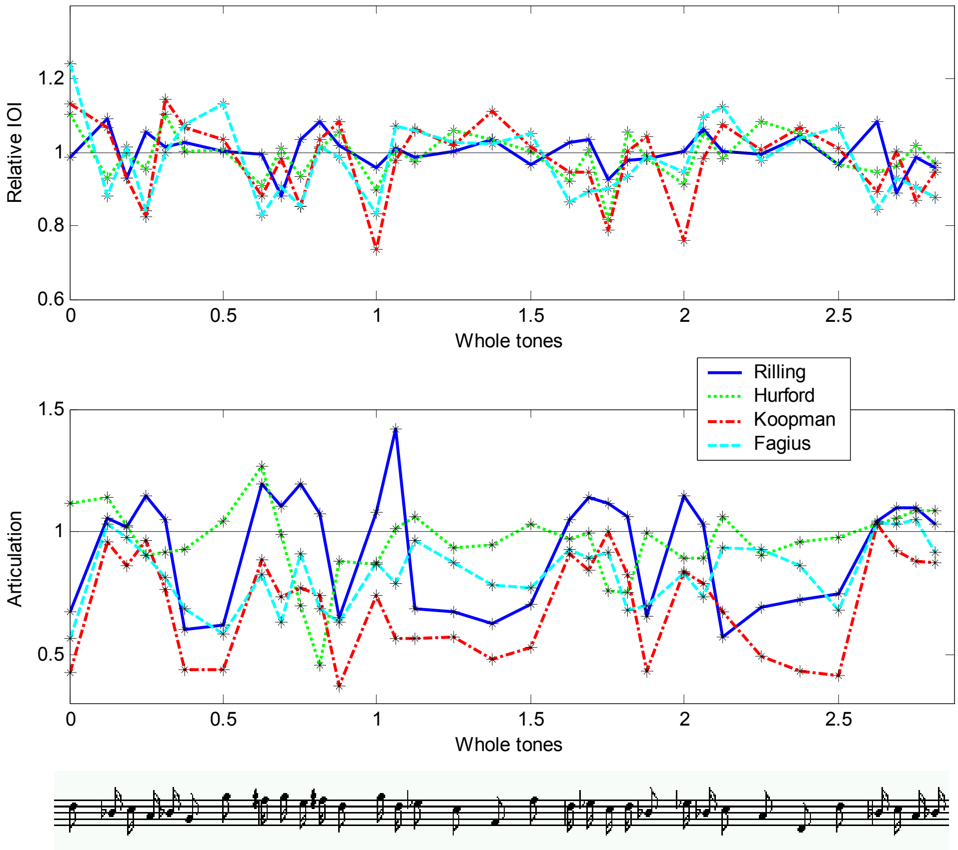
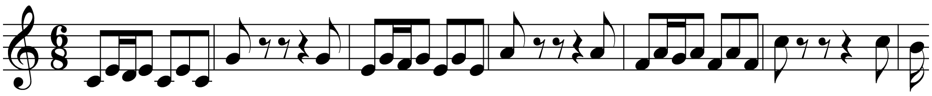


Figure 13: Relative IOI (top) and articulation (bottom) for all four performances of BWV 542.

BWV 564



In BWV 564 there are notated pauses in the theme. Please observe that notes preceding pauses have been excluded from analysis.

Hurford and Fagius: Staccato on weak beats

Hurford and Fagius show a clear pattern relating articulation and metrical structure: Notes coinciding with strong beats are played legato, others are played staccato. In 6/8 time, strong beats are on the first and fourth eighth-notes of each bar; the other notes are weak.

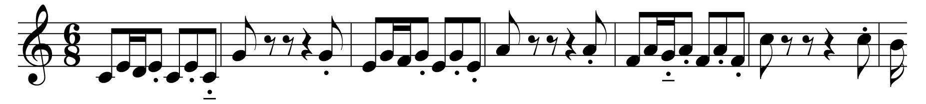


Figure 14. Articulation in BWV 564 for Hurford and Fagius. Staccato dots indicate articulations below 0.5 (for Hurford) or below 0.65 (for Fagius). Two tones are disputed.

Koopman and Rübsam: More staccato tones

Koopman's and Rübsam's articulations are similar to Hurford's and Fagius', but with even more tones made staccato. In particular, the fourth beat of each bar is played staccato. This was not the case with Hurford and Fagius. Koopman and Rübsam have very different "standard articulation" levels, their average articulation values being 0.65 and 0.86, respectively. Still, we see here another example of great similarities found in performers with very different average articulations. Figure 15 shows their articulations plotted against one another, Figure 16 shows the notated result.

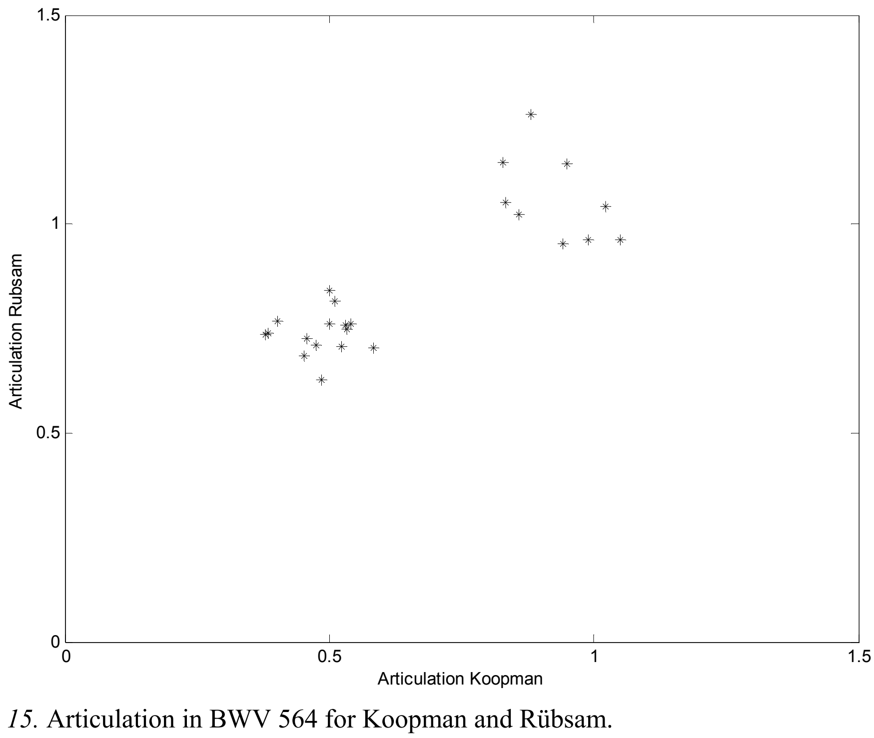


Figure 15. Articulation in BWV 564 for Koopman and Rübsam.

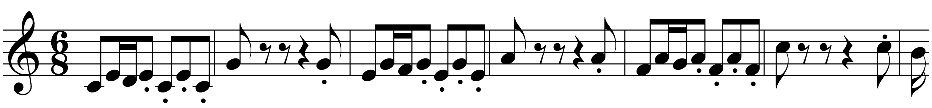


Figure 16. Articulation in BWV 564 for Koopman and Rübsam. Staccato dots indicate articulations below 0.6 (for Koopman) or below 0.85 (for Rübsam).

The upbeats
Here we find a very consistent pattern: All upbeats are played staccato in all performances. This is not very surprising considering the metrical articulation pattern exhibited by all performers in the rest of the piece. The upbeat is of course a metrically weak beat.

Summary
The BWV 564 theme consists of three rhythmically identical sequences. As seen in Figure 17 the similarity within performers between the sequences is quite high. The performers do not change their articulation strategy very much from one sequence to the next. All four performers stressed the metrical structure in their articulation.

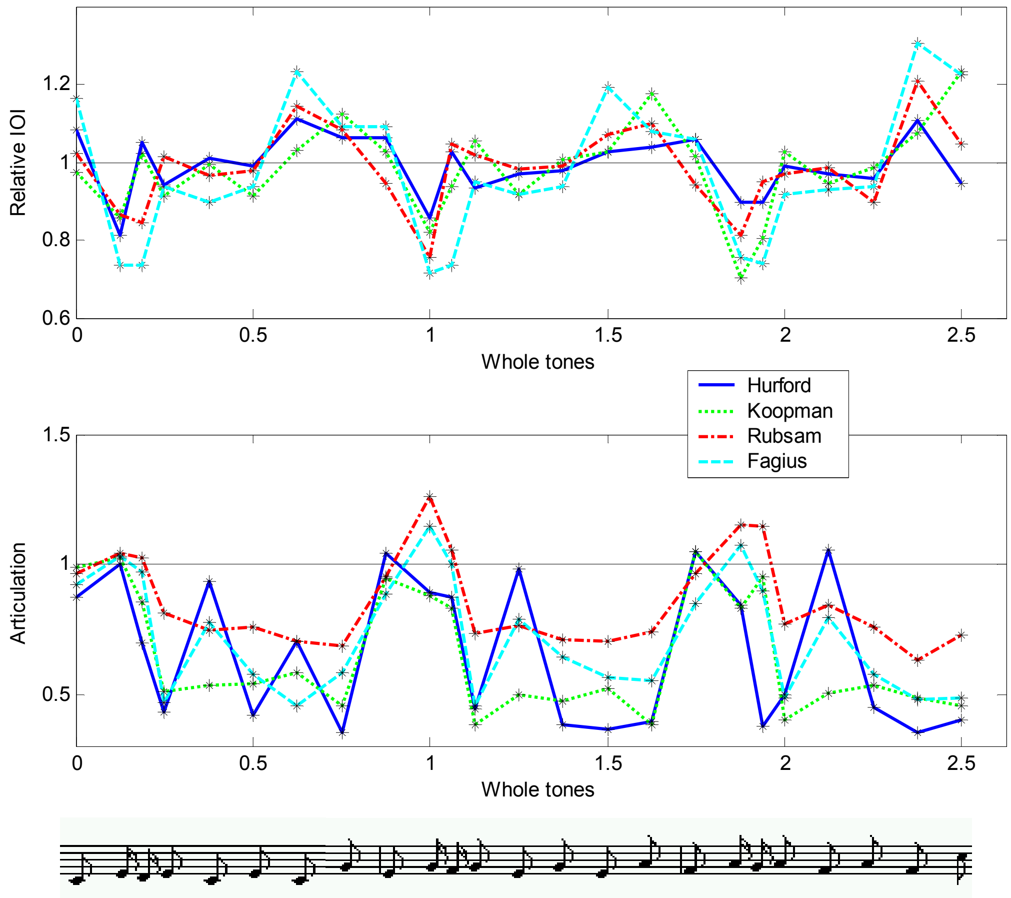
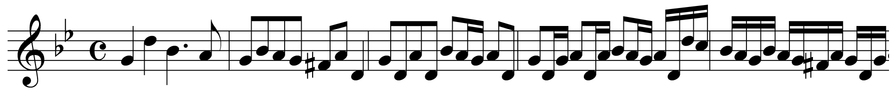


Figure 17: Relative IOI (top) and articulation (bottom) for all four performances of BWV 564. Please observe that notes followed by pauses have been excluded. This explains the metrically strange orientation notes at the bottom.

BWV 578



The BWV 578 theme is both rhythmically and melodically, but perhaps not harmonically, varied. It includes several leaps greater than or equal to a fourth.

Rübsam and Fagius: Partly similar articulation
In both Rübsam and Fagius, many staccato notes are metrically weak. They appear, for example, on the last eighth-note or on the last sixteenth-note of each beat (the theme is in common time, so there are four beats in each bar). In other words, they do not appear on the beats at all. This behaviour is very evident in Rübsam, although he also plays some other tones staccato. In Fagius, all staccato tones are of this kind, with only two exceptions

(the D in the 2nd bar, and the G in the fourth bar). So even though I have marked 21 notes staccato in Rübsam, but only 10 notes in Fagius, I would say that they share an overall strategy, shortening the articulation on metrically weak notes. Figures 18 & 19 show the notated result.

Figure 18. Articulation in BWV 578 for Rübsam. Staccato dots indicate articulation below 0.9.

Figure 19. Articulation in BWV 578 for Fagius. Staccato dots indicate articulation below 0.85

Rilling: Marking the ends of phrases

Rilling shows an almost uniform legato articulation throughout the excerpt. Scrutinizing his few staccato tones reveals that they appear at the end of bars 2 and 3. I believe this is Rilling's way of marking the phrase ends; he thus sees bars 1-2 as one phrase, bar 3 as one phrase, and bars 4-5 (or possibly even longer) as one phrase. Figure 20 shows Rilling's articulation in musical notes.

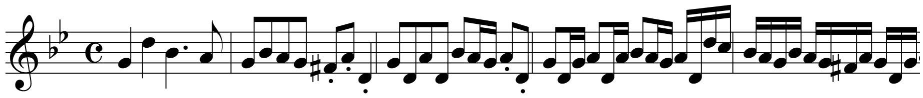


Figure 20. Articulation in BWV 578 for Rilling. Staccato dots indicate articulation below 0.8.

Comparison with DM punctuation

The correlations are very weak. This is specially disappointing since the implicit harmonic structure is very simple in this piece, implying that the melodic structure should suffice to produce a reasonable punctuation. (The DM punctuation rule as used here does not include any harmonic considerations.)

Summary

As in BWV 564, the main articulatory pattern in BWV 578 is the occurrence of staccato in metrically weak positions. However, one performer played legato throughout the theme, using staccato only at the end of phrases. Figure 21 shows all articulatory data in BWV 578.

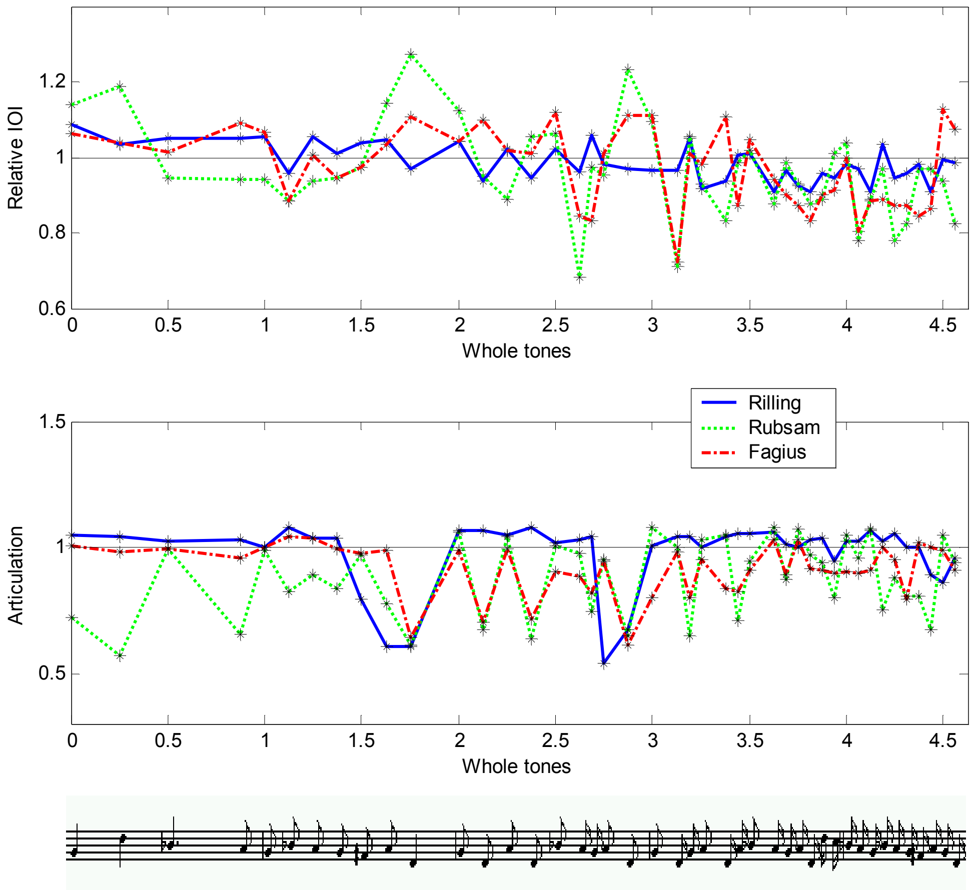


Figure 21. Relative IOI (top) and articulation (bottom) for all four performances of BWV 578.

Discussion and conclusions

This investigation has given some quantitative results. First, the mean articulation was 0.84. It is not easy to know how strongly influenced is the result from the type of instrument (organ) or from the type of music (Bach fugue openings). Articulation similarity, as measured by the mean correlation coefficient between performers, was 0.46. This should be compared to the relative IOI similarity of 0.52 (measured in the same way). The difference is too small to be statistically significant, but if it is real I believe it can be explained by the relative IOI being not only an articulation strategy, but most of all a phrasing strategy. Relative IOI adjustments act also on a larger scale, making them more robust.

Secondly, a negative mean correlation between articulation and relative IOI was found. The value –0.31 deviated significantly from zero with $p < 10^{-6}$, but again, it is difficult to assess the generality of this result. One thing was striking, though. For relative IOI’s below 0.9 there were no tones with articulation below 0.7. For relative IOI’s above 1.15, on the other hand, there were no tones with articulation above 0.7. Another notable result was that the values varied between performers, so that two out of five organists exhibited near-zero correlations.

A general result of more qualitative character is that performers may have different average articulation but still share the same articulatory strategy. Thus an articulation of 0.75 could be staccato for one performer, but legato for another. This might perhaps not be surprising, but it is nevertheless a basic result to keep in mind in all discussions on articulation.

Another result with potential generality is the occurence of binary articulation. This term means that the performer articulated each tone either short or long. The most clear examples were found in BWV 542 and BWV 564. One should note that both pieces involves eighth-notes and sixteenth-notes only. Still, there is no inescapable *a priori* reason to believe that binary articulation appears exclusively in pieces involving only two note-lengths. (Indeed, we found that Fagius used binary articulation in BWV 537.) The existence of binary articulation is interesting from a computer-control point of view, for it could facilitate successful simulation of realistic articulation. It would only be a matter of determining for each tone whether it is short or long. Within the two articulation groups the exact articulation values could be computed by adding or subtracting small random values so that not all tones in the same group (short or long) will get exactly the same articulation.

Yet another qualitative result is that notes in similar positions often are articulated similarly, i.e. there is an articulation consistency within each performer. This was particularly true for the BWV 564 theme, which is made up of sequential repeats. The finding is concordant with earlier results that the local tempo deviations (i.e. relative IOI's) are similar in music with repeats. See for example Gabrielsson (1987), p. 90ff.

Comparing the empirical articulations with the DM punctuation rule revealed a zero mean correlation. Of course, articulation is not identical to punctuation, but it is still reasonable to expect similarities to be exposed by the method used here, since insertion of commas strongly affects the articulation. One speculation is that the DM rule catches most punctuations in certain sections, but that a static rule cannot be used indiscriminately in all pieces. An idea like this gets some support from a recent paper investigating some of the DM features (Sundberg, Friberg & Bresin 2003).

Upbeats have been touched upon a few times. The only consistent finding within one piece was that all upbeats were played staccato in BWV 564. This is consistent with the general staccato articulation on weak beats in the rest of the theme. A more speculative possibility is that the performers want to detach the upbeat from the following tones because they belong to different chords. This theory must necessarily be speculative, since the chord progression is ambiguous in BWV 564. (Of course, the chord progression of a monophonic melody is always ambiguous.) In BWV 537 the opening upbeat is a C, leading to four G's in the first bar. Since the piece is in C minor, it is reasonable to attribute implicitely a C minor chord to both upbeat and the first bar. In BWV 542 the opening upbeat could be attributed a dominant chord (D major) leading to a G minor on the following B flat tone. If performers generally want to detach upbeats with different chords from the following tone(s), we should expect the upbeat of BWV 537 to be more legato and the upbeat of BWV 542 to be more staccato. Is this the case? Well, not really. In BWV 542 three performers out of four play staccato, but in BWV 537 two out of three also play staccato (where the opposite would have been nicer). The data material is too little to draw statistical conclusions in this matter. I believe that a hypothesis on upbeat chord attribuation could well be tested with a larger database.

All in all, we have ended up with a bundle of diverse results. To be fair, they are not contradictory, but neither do they point at any clearly dominant factor determining the articulation. Therefore, a working model should take many factors into account. I now wish to point out two possible models.

One would simply be a multiple linear regression model. Articulation A_n for tone n could for example be written

$$A_n = A_{mean} + c_1 IOI_n + c_2 relIOI_n + c_3 MW_n + c_4 PW_n + c_5 HW_n ,$$

where A_{mean} is a constant representing "normal" articulation (0.84 according to the present study), c_1, c_2, c_3, c_4 and c_5 are constants to be evaluated when testing the model, *IOI* is the inter-onset interval, *relIOI* is the relative IOI, *MW* is a metrical weight attached to each note according to some rules for the given time-signature, *PW* is a phrasing weight indicating whether the note is in the beginning or in the end of a phrase according to some rules, and *HW* is a harmonic weight (although the harmonic influence has not been assessed in the present study).[13] Possibly, the *PW* and *HW* parameters could be skipped, their contributions being largely inherent in the *relIOI* parameter. The input in this model is assumed to be a score including a tempo suggestion. As it turns out, then, the model is heavily dependent on the relative IOI's. The (absolute) *IOI*'s are roughly known, since we have the score and the tempo. The *MW*s can be calculated from the score. The *relIOIs* could be calculated from the performance rules in the Director Musices program (Friberg et al. 2003). If *PW* and *HW* are included in the model, they too should be possible to calculate using Director Musices. (There are rules in DM for phrase arcs, "harmonic charge", etc. But the *HW*s would require the chords to be spelled out in the input score.) We do not know how well a multiple linear regression model fits empirical data, and it is beyond the scope of this work to evaluate this. But it seems reasonable that it is a somewhat crude model, for the empirical findings in this study suggest that whereas some articulation patterns are concerned mainly with the metrical structure, others are concerned with the absolute or relative IOI, but hardly with all these things at the same time.

Therefore, a more sophisticated model, better adapted to computer simulations of articulation, would make the necessary calculations in a predetermined order. For example, if the piece is rather fast and contains only two notelengths, binary articulation could be appropriate. Longer tones could be attributed a mean articulation of, say, 0.65 and shorter tones could have the mean value 0.95. Within these two groups, each note would be assigned an exact articulation value by randomly adding or subtracting small values. In this way each note will have its own articulation value, but there will still be two clearly separated articulation groups.

If the piece is not suitable for binary articulation, another strategy has to be chosen. It could involve enhancing the metrical structure (as in Rübsam's and Fagius' performances of BWV 578), or the phrasing (as in Rilling's version of BWV 578), or both. It could involve detachment of upbeats (as in BWV 564 and most performances of BWV 537 and 542), shortening of repeated notes (as in the first bar of BWV 537). Whatever weights are attributed to these actions, the last check should be the relation between relative IOI's and articulation, removing legatos in tones with relative IOI above, say, 1.2 and removing clear staccatos in tones with relative IOI below, say, 0.85 (according to Figure 4).

In conclusion, even though musical articulation might be hard to model, it is well worth trying. The present study suggests that performers often articulate in comprehensible ways, but it is difficult to tell which strategy is to be chosen in a particular piece. Some of the strategies are mutually exclusive and yield non-identical results. Still the mean intra-performer correlation is almost as high for articulation as for relative IOI, the variations of which have been studied and modelled by many researchers. Articulation seems to be no more random than, say, phrasing, but it is certainly more complex.

[13] I have deliberately excluded intrument-specific factors contributing to articulation. For example, in piano playing the fingering can affect the articulation.

References

Battel, G. U. & Fimbianti, R. 1998. How Communicate Expressive Intentions in Piano Performance. *Proceedings of the XII Colloquium on Musical Informatics*, Gorizia, September 24-26, 1998, 67–70.

Bolzinger, S. 1995. *Contribution à l'étude de la rétroaction dans la pratique musicale par l'analyse de l'influence des variations d'acoustique de la salle sur le jeu du pianiste.* Diss., Institut de Mécanique, Université Aix-Marseille II, Marseille. (Exemplaire provisoire)

Bresin, R. & Battel, G. U. 2000. Articulation Strategies in Expressive Piano Performance. Analysis of Legato, Staccato, and Repeated Notes in Performance of the Andante Movement of Mozart's Sonata in G Major (K 545). *Journal of New Music Research* 29(3), 211–224.

Chew, G. 2001. "Articulation and phrasing", in *The New Grove Dictionary of Music and Musicians*, S. Sadie (ed.), vol. 2, p. 86–89. London: Macmillan.

Ferguson, H. 1975. *Keyboard Interpretation from the 14th to the 19th Century: An Introduction.* New York & London: Oxford University Press.

Forsblom, E. 1957. *Studier över stiltrohet och subjektivitet i interpretationen av J. S. Bachs orgelkompositioner.* Åbo: Åbo Akademi. Acta Academiae Aboensis, Humaniora XXIII.1.

Friberg, A. & Battel, G. U. 2002. Structural Communication. In: R. Parncutt & G. E. McPherson (eds.), *The Science and Psychology of Music Performance: Creative Strategies for Teaching and Learning*, 199–218. New York: Oxford University Press.

Friberg, A. et al. 2003. *Director Musices* version 2.4, developed mainly by Anders Friberg, Lars Frydén, Vittorio Colombo, and Johan Sundberg. Available free of charge at http://www.speech.kth.se/music/performance/.

Gabrielsson, A. 1987. Once Again: The Theme from Mozart's Piano Sonata in A Major (K. 331). In: A. Gabrielsson (ed.), *Action and Perception in Rhythm and Music.* Publications issued by the Royal Swedish Academy of Music No 55, 81–103.

Gabrielsson, A. 1999. The Performance of Music. In: D. Deutsch, *The Psychology of Music.* San Diego/London: Academic Press, 2nd ed., 501–602.

Gabrielsson, A. 2003. Music Performance Research at the Millennium. *Psychology of Music* 31(3), 221–272.

Hitech Development 2002. *Soundswell.* Information available at http://www.hitech.se/development/.

Jerkert, J. 2003. Measurements and models of musical articulation. *Proceedings of SMAC03 (Stockholm Music Acoustics Conference 2003)*, 537–541.

Juslin, P. N. 2001. Communicating Emotion in Music Performance: A Review and Theoretical Framework. In: P. N. Juslin & J. A. Sloboda (ed.), *Music and Emotion: Theory and Research*, 309–337. Oxford: Oxford University Press.

Juslin, P. N.; Friberg, A. & Bresin, R. 2002. Toward a computational model of expression in music performance: the GERM model. *Musicae Scientiae* Special issue 2001/2002, 63–122.

Keller, H. 1925. *Die musikalische Artikulation insbesondere bei Joh. Seb. Bach.* Veröffentlichungen des Musik-Instituts der Universität Tübingen. Stuttgart: C. L. Schultheiß Musikverlag.

Keller, H. 1955. *Phrasierung und Artikulation. Ein Beitrag zu einer Sprachlehre der Musik.* Kassel/Basel: Bärenreiter.

Keller, H. 1965. *Phrasing and Articulation: A Contribution to a Rhetoric of Music.* Translated by L. Gerdine. London: Barrie and Rockliff.

LaRue, J. 1992. *Guidelines for Style Analysis.* Pinewood, Michigan: Harmonie Park Press, 2nd ed.

Lerdahl, F. 1996. Calculating Tonal Tension. *Music Perception* 13(3), 319–363. [Reference quoted from Battel & Fimbianti (1998).]

Repp, B. H. 1992. 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.

Repp, B. H. 1995. Acoustics, Perception, and Production of Legato Articulation on a Digital Piano. *Journal of the Acoustical Society of America* 97(6), 3862–3874.

Repp, B. H. 1997. Acoustics, Perception, and Production of Legato Articulation on a Computer-Controlled Grand Piano. *Journal of the Acoustical Society of America* 102(3), 1878–1890.

Repp, B. H. 1998. Perception and Production of Staccato Articulation on the Piano. Unpublished manuscript, completed October 1998. Available on the Internet: http://www.haskins.yale.edu/haskins/MISC/REPP/Staccato.pdf.

Sjölander, K. and Beskow, J. 2002. *WaveSurfer*. Available at http://www.speech.kth.se/wavesurfer/.

Sundberg, J.; Friberg, A. & Bresin, R. 2003. Musician's and computer's tone inter-onset-interval in Mozart's Piano Sonata K 332, 2nd mvt, bar 1-20. *TMH-QPSR* 45, 47–59. Available at http://www.speech.kth.se/qpsr/tmh/2003/03-45-047-059.pdf.

Appendix: Matlab files

The most important Matlab files used in this work are reproduced below. Note: `iseven` and `isrowvector` are not standard Matlab functions but they perform quite obvious controls and are not reproduced here.

```
% ARTRES
%   Presenting plots of articulation measurements.
%   This function presents the results of articulation
%   measurements in two subplots: relative IOI (top) and
%   articulation degree (bottom).
%
%   Syntax: artres(avg, leg, lengthfile, player1, player2,
%   player3, ...),
%   where
%     avg = 0 or 1; 1 if you want an average curve to be drawn, 0
%       if not;
%     leg is a string containing the command for a suitable
%       legend,
%       e.g. leg='legend(''Player 1'',''Player 2'',0)';
%     lengthfile is a vector with the nominal tone lengths;
%     player1 is a vector with the onset and offset times for
%       player 1, etc.

function [] = artres(avg, leg, lengthfile, varargin)

N={varargin};
sizeN=nargin-3;

% Articulation
for i=1:sizeN
    art(:,i)=articul(N{1}{i});
end
n=size(art,1);
artmin=min(min(art)); artmax=max(max(art));

% IOI relative to nominal tone lengths
for i=1:sizeN
    relioi(:,i)=getrelioi(lengthfile,N{1}{i});
end
lmin=min(min(relioi)); lmax=max(max(relioi));

% Plotting everything
S={'b-' 'g:' 'r-.' 'c--' 'm-*' 'k:.'};
xaxis=[0; cumsum(lengthfile)];
xaxis=xaxis([1:length(xaxis)-1]);
xaxshort=xaxis([1:length(xaxis)-1]);
subplot(2,1,1),
for i=1:sizeN
    plot(xaxshort,relioi(:,i),S{(rem(i,length(S)))}),
    hold on
end
if avg==1
    plot(xaxshort,mean(relioi,2),'*-k', 'lineWidth',1.5), %average
end
```

```
axis([0 xaxis(length(xaxis)) lmin-0.1*(lmax-lmin) lmax+0.1*(lmax-
lmin)]),
plot([0 xaxis(length(xaxis))],[1 1],'k'),
%title('Relative IOI')
xlabel('Whole tones'), ylabel('Relative IOI'),
eval(leg)
subplot(2,1,2),
for i=1:sizeN
    plot(xaxshort,art(:,i),S{(rem(i,length(S)))}),
    hold on
end
if avg==1
    plot(xaxshort,mean(art,2),'*-k', 'lineWidth',1.5), %average
end
axis([0 xaxis(length(xaxis)) artmin-0.1*(artmax-artmin)
artmax+0.1*(artmax-artmin)]),
plot([0 xaxis(length(xaxis))],[1 1],'k'),
%title('Articulation')
xlabel('Whole tones'), ylabel('Articulation'),
eval(leg)
```

```
% ARTICUL
%   Calculating the articulation degree, i.e. the
%   tone lengths relative to the ioi (inter onset
%   interval).
%   Syntax: [art, ioi] = articul(filename)
%   where
%     art is a vector containing the articulation degree
%      values,
%     ioi is a vector containing the ioi values,
%     filename is the name of a function taking no input
%      but containing the onset and offset time values in
%      a vector; thus a call art=articul(foo) requires a
%      function foo to be defined with the following content:
%         function T = foo()
%         T=[on1 off1 on2 off2 on3 off3 ...];
%      where on1 is the onset time for tone no. 1, off1 is
%      the offset time for tone no. 1, etc.

function [art, ioi] = articul(filename)

error(nargchk(1,1,nargin));

% Loading file
T=filename;
% We want a column vector, not a row vector
if isrowvector(T)
    T=T';
end
N=length(T);
% N has to be odd
if iseven(N)
    error('The length of the time vector must be odd')
end
onsets=T([1:2:N]);
offsets=[T([2:2:N-1]); NaN];
tonedata=[onsets offsets];
ioi=diff(onsets);
tonelengths=tonedata(:,2)-tonedata(:,1);
tonelengths=tonelengths(1:length(tonelengths)-1);
```

```
art=tonelengths./ioi;
```

```
% GETRELIOI
%   Calculating the IOI's relative to the nominal tone lengths.

function out = getrelioi(lengthfile, timefile)

error(nargchk(2,2,nargin));

L=lengthfile;
% We want a column vector, not a row vector
if isrowvector(L)
    L=L';
end
ioi=getioi(timefile);
n=length(ioi);
L=L([1:n]);
out=(ioi/sum(ioi))./(L/sum(L));
```

```
% GETIOI
%   Calculating the IOI's.

function out = getioi(filename)

error(nargchk(1,1,nargin));

[dummy, out]=articul(filename);
```