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* The title is a paraphrase on Edsger W. Dijkstra's note in the March 1968 "Communications of the ACM", named "Goto Statement Considered Harmful". It stressed the importance of structure in computer programs. Knowing this, the parallel with unstructured representations of tempo (like tempo curves) is obvious.

TEMPO CURVES CONSIDERED HARMFUL

Peter Desain & Henkjan Honing

In which we decided to have a good time, invited an expert, and had our first disappointment.

Not so long ago we decided to spend a Christmas holiday studying music and its performance. One of us is an amateur mathematician (M) and the other one likes to delve into old psychology textbooks (P), and because we enjoy impressing each other with new facts and insights, we often find ourselves in vehement discussions. Therefore we thought we might have a pleasant and peaceful time by putting our beloved hobby horses aside and embark upon a subject about which neither of us knew much: the timing aspects of music. We became interested in this field because we had noticed, while playing with the computer, our favourite toy, that adding just a bit of random timing noise to a program that played a score in an otherwise metronomically perfect way, made the music much more pleasant to listen to. It seemed as if we could make more sense of it. But we suspected that there was more to timing and expressive performance than adding bits of noise, so we invited a mutual friend who is a retired professional pianist to spend Christmas in our small but well equipped laboratory. Our friend has a great love for the piano and its music, but is completely ignorant of the advances of modern technology. To demonstrate to him our latest sequencer program we asked him to play the theme from the six variations composed by Ludwig van Beethoven on the duet *Nel cor più non mi sento*, the score of which we had lying around (see Figure 1).



Figure 1. Score of the theme of Nel cor più non mi sento.

Even though he was somewhat disturbed by the touch and harpsichord-like sound of the electronic piano, he was quite fascinated with the possibility of recording and playing back on the same instrument. Enthusiastically we told him that this system was more than just a modern version of the pianola: 'You can examine and change every detail you want; for instance, inspect the timing, accurately to the millisecond, add and remove notes, make notes longer or shorter, or louder or softer, and so on and so forth.' Our friend became quite excited and asked: 'Could your machine play my performance in a minor key?' We were a bit put off by the simplicity of his demand, but patiently demonstrated the key-change feature. After hearing his performance with the key changed to G minor our friend was not impressed. 'O dear, I'm afraid this sounds much too hasty. For example, the "dramatic" e-flat in bar 3 needs more time. Let me play it in minor for you.' When we looked at the timing data of his new performance it indeed showed a different pattern. Upon noticing our disappointed faces our friend remarked 'this was not a minor change; it really turns it into another piece. We did not expect your device to know about that, did we?' We kept silent. 'But your machine can undoubtedly play the same piece at a faster tempo.' That set us in motion again. We changed the setting of the tempo knob to a tempo one-and-a-half times as high and pushed the play button. The face of our friend again did not show the expression we had hoped for. 'I'm awfully sorry, but this is not right! It sounds like a gramophone record played at the wrong speed, but without changing the pitches.' Suspiciously, we wanted some proof for his crude statement and asked him to play it the way he thought it ought to be performed. His version at the higher tempo was indeed different. We had to admit that it sounded more natural than our artificially speeded-up version. What made it sound so much better? We tried to unravel this mystery by examining the timing of the onsets and the offsets of the notes, since these were the variables that could be altered with our electronic keyboard, just like a real harpsichord.

Tempo, Metre and Beat

Temporal pattern is a series of time intervals, without any interpretation or structure.

Rhythm is a temporal pattern with durational and accentual relationships and possibly structural interpretations (Dowling & Harwood, 1986).

Beat refers to a perceived pulse marking off equal durational units (Dowling & Harwood, 1986, p. 185). They set the most basic level of metrical organisation. The interval between beats is sometimes called a “time-span” (Lerdahl & Jackendoff, 1983), or, less abstract, beat duration, beat period or metrical unit (Longuet-Higgins & Lisle, 1989).

Metre involves a ratio relationship between at least two time levels (Yeston, 1976). One is a referent time level, the beat period, and the other is a higher order period based on a fixed number of beat periods, the measure. It imposes an accent structure on beats, because beats initiating higher level boundaries are considered more important.

Tempo refers to the rate at which beats occur (often expressed as beats per minute), and is therefore closely linked to the metrical structure.

Density is used to refer to the average presentation rate taken across events of different duration (i.e. events per second) when a piece has events of different durations and the beat is hard to determine unambiguously, if at all (Dowling & Harwood, 1986).

It is important to note that rhythm, tempo, metre and density can be conceived independently: it is possible to maintain the same tempo while changing density; for example, a musical fragment can have a lot of embellishments (i.e. have a high density) and still be perceived as having a slow tempo. Furthermore, rhythm can exist without a regular metre and any type of rhythmical grouping can occur in any type of metrical structure (Cooper & Meyer, 1960).

Tactus is the tempo expressed at the level at which the units (beats) pass at a moderate rate (Lerdahl & Jackendoff, 1983). This rate is around the “preferred” or “spontaneous” tempo of about 100 beats per minute (Fraisse, 1982).

Our sequencer, a very recent version, had a separate tempo track. In this track, the tempo can be changed from fragment to fragment, even from note to note. With this feature we could put the original score on one track and the timing of the performance, expressed as tempo changes per note, on the tempo track, although it took quite a bit of calculating and editing by hand. After a while we had completely recreated the original performance, but now as a score plus a separate track of expressive timing

information. This tempo track looked like the graph in Figure 2a (for clarity we show only the timing of the melody). We could now compare the timing of this performance with the one played at tempo 90 (see Figure 2b). Their form was quite different even by visual inspection, although our ears were, of course, the only valid judges.

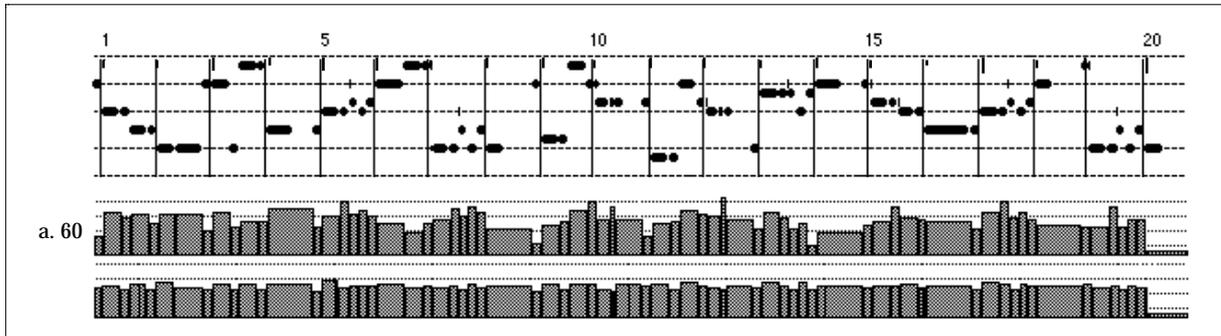


Figure 2. Tempo deviations in the performance of the theme at tempo 60 (a) and at tempo 90 (b).

What had happened? The sequencer had speeded everything up by the same amount (which we all agreed sounded awkward), while in the performance the expressive timing appears not to scale up everywhere by the same factor. Our friend adapted his rubato according to the tempo, which he explained to us: ‘My timing is very much linked to the musical structure and what I want to communicate of it in an artistic manner to the listener. If I play the piece at another tempo, other structural levels become more important; for instance, at a lower tempo the tactus will shift to a lower level, the subdivisions of the beat will get more “in focus”, so to say, and my phrasing will have much more detail.’ After some scratching with pen on paper, M found a quite elegant way of representing these changes using simple mathematics. We took the time interval between the onsets of every two succeeding notes and calculated the ratios of these time intervals in the two tempi. If the expressive timing pattern would scale-up linearly, we would find the ratios for all the notes to be around the ratio between the two tempi, and most ratios were indeed around 1.5. There was some variance around that factor, though, and we thought that could be explained by the more elaborate short-span phrasing at the lower tempo. But, even more noticeable was the fact that for some notes the ratio was close to 1. We found that these notes were notated as grace notes in the score. They did not change at all when performed at an another tempo. We also found that not all grace notes behaved like this. For example, the two grace notes that cover an interval of a sixth, in bar 7 and 19, were timed like any other note: they were actually played in a metrical way. Our pianist got really excited about our observations. He pointed at grace notes in the score that were notated in the same way, but that needed a different interpretation, and he started to lecture about the different

kinds of ornaments, so popular in the eighteenth century, the difference between *acciaccatura* and *appoggiatura*, 'ornaments that "crush in" or "lean on" notes', about their possible harmonic or melodic function changing their performance, and so on and so forth. When he noticed that we were getting bored with his lengthy historical observations, he woke us up again with a new, sharp attack on our beautiful sequencer program: 'It might be forgivable that your program cannot play the onsets of ornaments correctly, but it also murders the articulation of most notes, especially the staccato ones. And have you heard what the program did to my detailed colouring of the timbre of chords?' Well, in fact, we had not, but we could well understand that the timbral aspect brought about by the chord spread (playing some notes in a chord a tiny bit earlier or later than others) was not kept intact when all timing information is just scaled by a certain factor. And we did not even dare to play the performance again at a lower tempo, afraid that each chord would turn into an arpeggio.

So our sequencer was not so wonderful after all. It could not be used to *change* something, not even such a minor thing as the key in which the piece was played. Again our pianist explained that a change of key was not a minor thing. The minimal variation that he could think of was the repetition of bars 5-8 at the end of the theme. 'The only difference between them is the fact that the second segment is a repetition of the first, and I even expressed that minimal aspect by timing. This problem is exacerbated if the difference between two sections is the overall tempo. Then detailed knowledge about structural levels, articulation, timing of ornamentations and chords, is indispensable.' We had to agree. How dumb of us, after all, to assume that a tempo knob on a commercial sequencer package could be used to adjust the tempo.

Tempo, Timing and Structure

In principle, timing can be linked to any musical structural concept. The most concrete of those are the following.

Although the most obvious *metrical units* are bar and beat, this strictly hierarchical structure may extend above and below these levels. Special expressive marking of the first beat in the bar, either by timing, dynamics or articulation, is a common phenomenon (Sloboda, 1983).

Phrases may not be ordered in a strict hierarchy, and may cut across metrical structure. Phrase final lengthening is the most well-known way in which they are treated (Todd, 1989)

A large proportion of the timing variance can be attributed to *rhythmical groups* (Drake & Palmer, 1990). Some standard rhythmical patterns, like triplets, seem to have a preferred timing profile (Vos & Handel, 1987).

Small timing asynchronies within a *chord* (called chord spread) are perceived as an overall timbral effect - the actual timing pattern is hard to perceive.

Ornaments, like *grace notes* and *trills*, can be divided in *acciaccatura*, so called timeless ornaments, and *appoggiatura*, ornaments that take time and can have a relatively important harmonic or melodic function. The former normally falls outside the metrical framework, the latter tends to get performed in a metrical way.

The independent timing of individual *voices* is sometimes hard to perceive because their components are immediately organised by the perceptual system in different streams (Bregman, 1990). This is not the case with (almost) simultaneous onsets that result in clear timbral differences. This can be heard in ensemble playing where often the leading voice takes a small lead of around 10 ms. (Rasch, 1979).

Any *associative relation*, e.g. between a musical fragment and its repetition, can be given intentional expression by using the same or different timing patterns.

Wherein we looked at multiple performances, learned from a conductor and tried different hierarchies but had no success.

But we were convinced we could make our friend happy, and proposed to program some additions to the sequencer ourselves. We showed him a video tape about research done at MIT by Barry Vercoe and his collaborators on computer accompaniment of a real musician. In this project the computer is given a score and several performances of the piece. With that information it can be “trained” to follow and accompany the musician.

Not that we were trying to do that, but we could use the idea to annotate each note in the score with its deviation in the performance, in our case in different tempi. Our friend friendly agreed to perform the Beethoven theme at four different tempi that were musically acceptable to him. We saw again that some notes exhibited a large change when tempo is changed, while others were less influenced by the tempo. But we could now use statistical methods to derive the right timing information for each tempo from this data. Our friend, who started to develop a little bit of suspicion, asked: 'Will that solve playing at different tempi then?' We were not quite sure. We definitely had more information now, but the representation of the music was still flat; no structural information was provided. It seemed we could not avoid incorporating some organisation above the note level into our program. Our friend agreed with a smile that was almost saying: 'are you stupid or am I?' We got a bit nervous. But after some discussion he agreed to concentrate on the timing of simple structural units like beats and bars only, leaving the note by note details aside for the moment.

Then we remembered Max Mathews working at CCRMA, Stanford University, who does important work in conductor systems (sort of the opposite of what Vercoe is doing). He made a system where one can conduct a sequencer on the beat level, which was just what we needed. The idea of a conductor shook our friend up; that sounded a much better approach than all those statistics we tried to explain to him before. We gave our friend an electronic baton, connected to our sequencer, and asked him to conduct the piece. In the score in the sequencer the beats were marked. The program followed the conductor by aligning each conducted beat with the corresponding mark in the score, and it tracked the tempo indicated by the conductor in doing so. At the high tempo, beating the baton very quickly, it seemed all right, but at the moderate tempo it was impossible to steer the timing deviations within the beat. 'It sounds too jumpy,' our friend complained. Since the beat level of the system of Mathews is arbitrary (he calls it 'generalised'), we annotated the score with marks at a lower metrical level, which alleviated the problem a bit. But, as our friend was still complaining about the controlability, we eventually ended up by marking each note in the score. This gave complete control at last, though our poor pianist, out of breath by the acrobatics needed to draw each note out of the sequencer by means of a single baton, made a cynical remark about the wonderful invention, which we may have heard of, called a keyboard. We became a bit vapid and proposed to help our conductor by connecting three MIDI batons to the computer, the first two used by us to time the bars and the beats, and the third to be used by our friend to fill in the details, using batons inter-connected with a complex mechanism of wires, to keep the timing at all levels consistent. We fantasized for some

time about a whole orchestra of conductors, leading one pianist before them. It was clearly time for a tea break.

Timing and Tempo, Patterns and Curves

In studying *timing deviations* a first distinction should be made between non-intended *motor noise* and intended *expressive timing* or *rubato*. The first category deviates in the range of 10 to 100 ms; the latter can deviate up to 50% of the notated metrical duration in the score.

Expressive timing is continuously variable and reproducible (Shaffer, Clarke & Todd, 1985) and clearly related to structure (Clarke, 1988; Palmer, 1989).

It is important to note that there is interaction between timing and the other *expressive parameters* (like articulation, dynamics, intonation and timbre). For example, a note might be accented by playing it louder, a fraction earlier than expected or by lengthening its sounding duration. Which method of accentuation is used is difficult to perceive, even when the accentuation itself is obvious.

To refer to expressive timing, in computer music the term *micro tempo* is often used, comparable to the term *local tempo* used in the psychology of music (the tempo changes from event to event, expressed as a ratio of a performance time interval and a score time interval). For clarity, the term *timing* would be more appropriate here. It specifies the timing deviation on a note-to-note basis and is often referred to as the *expressive timing profile* (Clarke, 1985; Shaffer, 1981; Sloboda, 1983), *timing pattern* or *rubato pattern* (Palmer, 1989).

In these patterns, points are often connected, either stepwise with straight line segments or with a smooth interpolation, yielding a *timing curve*. Only the first representation maintains a proper relation with the time map in which points are connected with line segments. These continuous time maps are used by Jaffe (1985) and most people of the computer music community. Time maps can be superimposed, using one for each voice.

Time maps can also be constructed for uniformly spaced units in the score like bars or beats. The corresponding duration patterns form a true *tempo pattern*. The points in these patterns can be connected by line segments, yielding so called *tempo curves*. Some authors insist on stepwise tempo changes, like Mathews (Boulanger, 1990), in which they are linked to one level of the metrical structure.

Over tea our friend told us about a series of programs on BBC radio, presented by the English conductor Denis Vaughan, on the composer's pulse he used in conducting. The pulse is a hierarchical, composer specific way of timing the beats. This pulse was an idea proposed and actually programmed by someone working in Australia. We went to our library and looked for some references that might tell us more on this composer's pulse. We ran into a collection of articles by Manfred Clynes who had invented the notion. This pulse, coincidentally, had precisely the characteristics we were looking for: hierarchical tempo patterns linked to the metrical structure. It basically entailed a system of automated hierarchical batons, and reduced the complexity further by postulating a fixed pattern for each baton. We took a final sip of our tea and hurried back to the lab and added Clynes' Beethoven 6/8 pulse as tempo changes in the tempo track to our sequencer. It divided the time for each bar into two unequal time intervals for the first and second half-bar and divided each half-bar into 3 unequal parts, one for each beat. With some adjustments here and there, we had our program running in no time. We called in our musical friend from the library to provide some professional judgements. He was definitely not unhappy with the result. 'This sounds much better than the things I've heard before,' he said.



Figure 3. Score of the first variation of *Nel cor più non mi sento*.

'Let's do the first variation, and see how our system performs it,' our friend said, far more optimistic now. He was talking about "our" system. This was a good sign. 'This variation is written in an ornamental style,' our friend explained, while we loaded the score of the first variation (Figure 3) into our system and created the tempo track containing the Beethoven pulse for this material. 'The metrical and harmonic structure is the same for both theme and the first variation. The only difference is that there are more "ornamental" notes added,' he said in a patronizing tone. When everything was set we played him the result. 'Well, this is disappointing,' was his short and decisive answer. After seconds of uncomfortable silence he added, 'it lacks the general phrasing and detailed subtlety I think is essential to make it an acceptable performance. The rhythmical materials of the theme and the first variation are different. The sixteenth notes of the variation ask for a different kind of timing than the mainly short-long, short-long, short-long rhythm of the theme. This pulse plays only with the metrical structure, but musical structure has far more to offer than that.' So the composer's pulse could not just be mapped onto any rhythmic material. Furthermore, it only linked timing to the meter, and, as our friend made clear, phrasing and other musical structure was ignored.

That rang a bell. We remembered one of the articles by Neil Todd on a model of rubato, linked to phrase structure. His proposal is very similar to Clynes; it explains timing in terms of a hierarchical structure, but now phrase structure is the basic ingredient. The beat is again the lowest level; below that no timing is modelled. The abundance of mathematical notation in Todd's articles did not put off our amateur mathematician. Quite the contrary. 'This, on first sight, will give us a solid basis to work with. What he states here is that, if you remove all the constants from the formula, it is actually quite simple,' M said. 'Todd proposes to attach a parabola to each level of the hierarchical phrase structure, and sum their values to calculate the beat length.' He simplified a formula, found an error on the way and finally the model became easy to implement. We were quite conscious of the fact that we were the first really to hear Todd's model (he himself had never listened to it). It did not sound very pleasing because this model was expressed in terms of the phrase structure only (based on the idea of systematically lengthening the end of a phrase in a hierarchical way), and because it lacked all expressive timing below the level of beats.

Longing to show our collaborator that the computer could, in principle, also calculate detailed note-by-note timing, we looked for a model that would provide these. Happily we found masses of rules for those subtle nuances in the articles of Johan Sundberg and his colleagues. These rules formulated simple actions, like inserting a small pause in between two notes or shortening a note. The actions had to be performed

if the notes matched a certain pattern, such as constituting a pitch leap or forming part of a run of notes of equal duration. In fact there were so many rule sets proposed in his articles that we got a bit lost in the details, but it has to be said that some rule-cocktails really seemed to work for our piece. Especially if their influence was adjusted to effect a subtle change only, the music gained some liveliness. But because these rules are based on the surface structure of the music only we could predict the judgement of our musical expert by now. And indeed he did not even bother to comment on the artificially produced performances. Instead he kindly reminded us that we might give up looking for a system that enabled us to generate a “musically acceptable” performance, given a score (that is what Clynes, Todd and Sundberg are aiming at), for the simple reason that we already had an “acceptable” performance, namely his own. It was true, the initial aim of our endeavour was to find ways of manipulating the timing in a musically and perceptually plausible way, given a score *and* a performance. Because the simple representations we had used proved unsuccessful, we had been sidetracked by studying even simpler representations that could at most model a small aspect of our friend’s performances. We decided to close the session, look for more details in the literature, and give it another try the next day.

Generative models

Clynes (1983; 1987) proposes composer specific and metre specific, discrete tempo patterns. This so called composer's pulse is assumed to communicate the individual composer's personality. E.g. in the Beethoven 6/8 pulse the subsequent half-bars span 49 and 51% of the bar duration and each half bar is divided again in 35, 29 and 36%. Clynes is opposed to analysis of performance data: the pulses stem from his intuition. Repp (1990) has undertaken a careful evaluation of this model.

Todd (1985; 1989) proposes an additive model in which beat duration is calculated as a summation of parabola shaped curves, one for each level of hierarchical phrase structure. He complemented the model with an analysis method that calculates phrase structure from beat durations.

Sundberg et al. (1983; 1989) proposes a rule system to generate expression from a score based on surface structure. His research was done in an analysis-by-synthesis paradigm and captures expert intuition in the form of a large set of these rules. An example of a rule is "faster uphill": A duration of a note is shortened if it is preceded by a lower pitched note and followed by a higher pitched one. Van Oosten (1990) has undertaken a critical evaluation of this system.

In which we investigated discrete patterns and continuous curves, tried interpolation and failed again.

We found all kinds of references in the literature and read a lot that evening. It was amazing to find how much work actually was done on a problem that we had thought was not a problem at all. We became a little bit more conscious of the whole thing. It looked as if P's hobby horse, psychology, had to be given a chance. He explained that the perception of time had been modelled postulating a certain (often exponential) relation between objective time and experienced time. But this research had all been done with impoverished stimulus material, often consisting of just one time interval marked-off with two clicks. 'Other research,' P added, 'found that duration judgment depends on the way the interval is filled with more or fewer events, so unfortunately these simple laws cannot be directly applied to more complex material like real music.' Even P was disappointed with the results of his beautiful science. 'But psychology has something to offer to us here', he spoke in a defensive tone. 'Take a look at all the articles that present timing or tempo measurements in the form of continuous curves instead of just a scattergram of measurements. These curves more or less imply an independent existence, apart from the rhythmic material where they were measured

from. But psychological research has shown that one cannot perceive timing without events carrying it.' He found this convincingly argued in an article by the psychologist James J. Gibson called "Events are perceivable but time is not". 'Can you imagine perceiving a rubato without any notes carrying it?' P asked. 'And vice versa: "filling up" time by adding an event between two measured points is problematic, isn't it?' There seemed to be no possible argument.

Subjective Time, Duration and Tempo Magnitudes

Most psychophysical scales for time intervals are described by Stevens' Law, that relates the physical magnitude of a stimulus to its perceived magnitude as perceptual-time = a-constant.physical-time^{b-constant}. The *b* value differs from one dimension to the other. For time duration *b* is commonly found to be 1.1, slightly over estimation of the interval. However, for intervals shorter than 500 ms it is found that *b* is around 0.5, the square root of its physical duration (Michon, 1975).

Humans seem to have a relatively poor ability for time discrimination of intervals presented without context. The just notable differences (JND) are in the range of 5-10% (Woodrow, 1951) with an optimum near 600 ms intervals. However, in the context of a steady beat, the JND's are around 3% with the same optimum interval (Povel, 1981).

Much research was done on the existence of a spontaneous tempo, preferred rate or natural pace (Frasse, 1982). This tempo should occur as a preferred rate of spontaneous tapping, and material presented at that rate should be easy to perceive and remember. There is weak, but converging evidence for the existence of such a rate, again with intervals around 600 ms. There is no consistent evidence for physiological correlates like heart rate.

There has been quite some research done on the influence of different dimensions on time perception, mainly in the fifties. Evidence was found that, in general, the higher pitched the sound the longer the percept (Cohen et al., 1954), and the same holds for louder sounds (Hirsch et al, 1956). Evenly divided intervals seem longer than irregular divided ones (Ornstein 1969).

Time intervals shorter than 120 ms, preceded by a physically shorter neighbour time interval, are underestimated to such a remarkable degree that one can speak of an auditory illusion (Nakajima et al., 1989).

We decided to do the acid test using a feature of the sequencer program. In this program it was possible to copy tempo tracks from one piece to the other. We applied

the tempo track of the original performance of the theme (see Figure 2) to the score of the first variation. The result was poor; even we could hear that. The timing made sudden jumps, like a beginner sight-reading and hesitating at unexpected points because of a difficult note. The expressive timing pattern found in the theme did not “fit” the variation. Our friend’s performance of the variation was much smoother and had gestures on a larger scale, as far as we were able to judge (Figure 4). Also, the other way around, taking the timing data from the variation and applying it to the score of the theme had the same awkward effect. It seemed impossible to just add or remove notes using these stepwise tempo curves. We felt stupid again for having assumed that the independence of tempo tracks in the sequencer made musical sense. But it made us look in the literature for alternatives.

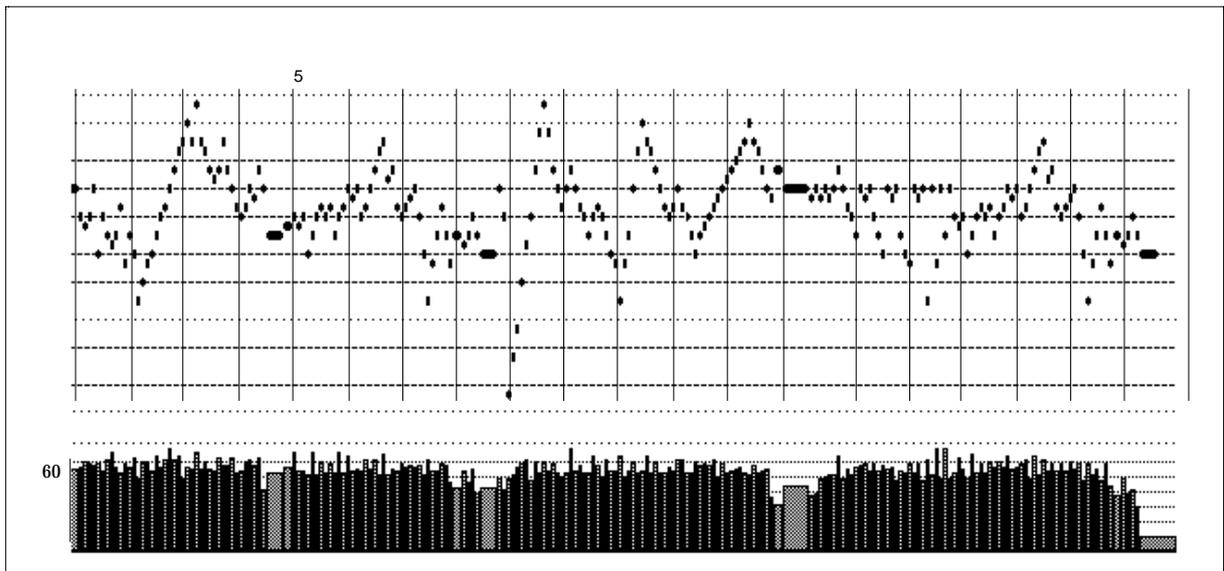


Figure 4. Tempo deviations in the performance of the variation at tempo 60.

The answer was not far away. In the field of computer music research continuous rubato curves were used almost by default. We decided to take the path of the continuous timing functions, hoping it would get rid of this awkward “jumpiness”. Thus M’s hobby horse was brought out again. ‘Functions are far easier to handle. One can calculate, given the right kind of function, a good timing curve for every piece,’ M argued convincingly. This combined approach of formality (in the mathematical sense) and pragmatics reminded us of a method developed by David Jaffe of CCRMA to model the timing of different parts of a computer orchestra. Jaffe wanted the different instruments to have their own timing, but they had to synchronise at specific points as well. By using a time map, instead of tempo changes, coordination and synchronization became possible. ‘What he actually does is to specify the timing for each event by

means of a function from score time to performance time,' M explained, 'a blatantly simple idea indeed: to integrate velocity or one-over-tempo, as Jaffe calls it, to get time. This of course restrains the possible functions one can use to make up such a time map; they have to increase monotonously and one must be able to calculate a first derivative.' This was again a method, among many others, in which different authors presented their ideas of tempo curves (see Figure 5). We tried to bring some order to the ways the different representations were used.

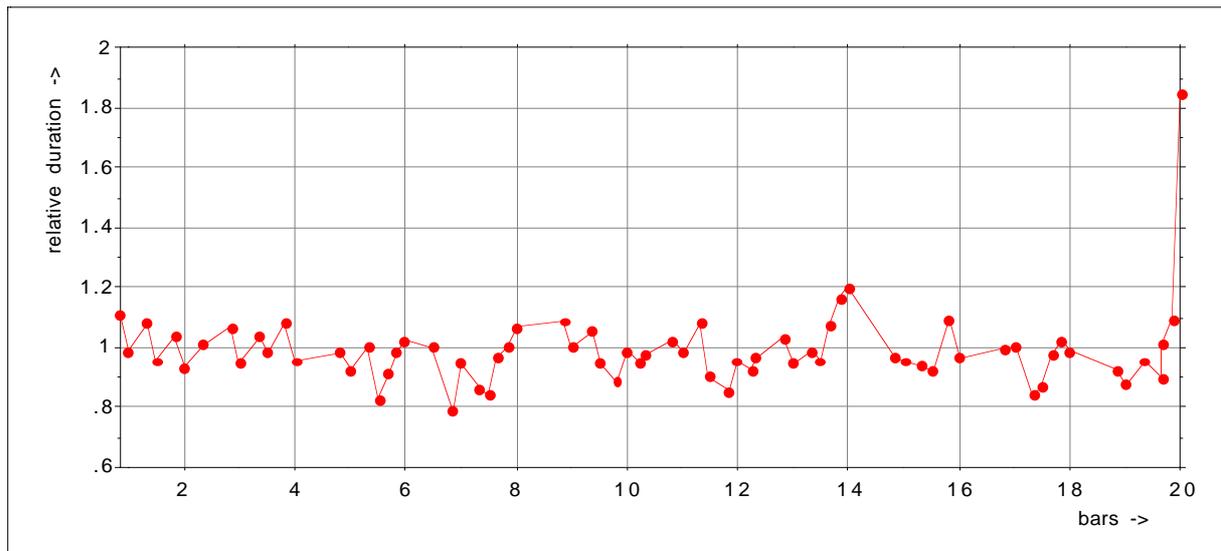


Figure 5. A typical so called "Tempo Curve" with duration factors for each note as a function of metrical time.

Soon M gave up, stating that it was a hopeless mess; no two authors used the same dependent and independent variables and measurement scales. And while in the end all the information needed could be extracted from most presentations, it was a difficult job, the more so because of the confusion in terminology. We decided to return to the practical application of the time map. We adapted the sequencer's tempo track to contain a time map (composed of line segments) instead of the discrete tempo changes we had used before. We then applied this continuous curve to the variation and had our pianist judge it. He thought it was much better than the direct application of the discrete curve of the theme to the variation. The interpolation (with line segments) did improve the smoothness of the timing, but he still complained about the sudden tempo jumps at the junctions of the curve. M remarked that one could restrict the allowed tempo map functions further or smooth the existing function, for instance, with splines. This brought us to an article describing work done at IRCAM by David Wessel and others, which indeed proposes the use of splines. We took an algorithm we had lying around that did splines and added it to our tempo track algorithm. And there it was:

with some twiddling of the parameters we could interpolate the timing pattern of the theme for its use on the variation. We almost thought that with this interpolation we had proven Gibson wrong. There was a smooth sense of timing in between events, and if one is smart enough one can tap it and hook new events onto it in a reasonable way. But our musical friend did not agree 'Reasonable?' he reacted angry, 'it sounds reasonable, yes, but your numerical calculations have nothing to do with the way I played it, whatsoever. The musical structure, my dear friends, remember the musical structure. How often do I have to repeat this. Timing *is* related to structure!' We suggested to him a cup of tea, in the hope that this would calm him down.

Objective Time, Duration and Tempo Measurements

When an event happens (an onset of a note) one can measure the *real time* elapsed since the beginning of the piece (called *performance time*) and also the point in the score where this onset was notated (called *score time*). The latter can be measured either in seconds (taking the tempo marking in the score serious, or normalising the total score length to the performance), in metrical units like beats or quarter notes (called *metrical time*), or as an event count (called *event time*). The last loses so much information that the timing pattern cannot be reconstructed without reference to the score.

Performance time can be shown as a function of score time (called a *time map*), or vice versa. In these representations it is easy to spot (a)synchronies between voices because they depict points in absolute time.

Calculating differences between subsequent performance times in a time map makes the step from time to duration. Because in such a representation it is difficult to compare notes of different nominal duration, a proportional measure is better. It makes the step from duration to relative duration by dividing two corresponding durations. In case a performance duration is divided by a score duration, this forms a series of duration factors (often misleadingly called tempo). This measure is mostly notated in a graph with the independent axis labelled with metrical or event time. In the case of the inverse calculation, the ratios form the velocity, the local speed of reading the score.

In both cases the measured points are often filled in with line segments - implying the existence of a tempo measurement in between events. This is misleading - the more so because integration does not yield the original time map again.

Gabrielsson (1974) uses note duration expressed in proportion to the length of the bar. This allows for comparison with exact note values in different meters. The method might be generalizable to study timing at different levels of structure.

Tempo is sometimes presented on a logarithmic scale; this is a first step towards the use of subjective magnitudes.

An interesting hypothesis was given by Brown (1979). He argues that a musician makes use of a collection of discrete tempi: a collection of discrete physically possible tempi, where the choice is defined by musical and performing factors.

EPILOGUE

What this partly fictitious story (the characters are fictitious, but the examples and arguments are real!) shows is that we have to be aware of the Tempo Curve. Of course

one should be encouraged to measure tempo curves and use them for the study of expressive timing. But it is a dangerous notion, despite its widespread use and comfortable description, because it lulls its users into the false impression that it has a musical and psychological reality. There is no abstract tempo curve in the music nor is there a mental tempo curve in the head of a performer or listener. And any transformation or manipulation based on the implied characteristics of such a notion is doomed to fail.

That does not mean that generic models that represent timing in terms of some sort of structure, even when they describe just a fraction of the many aspects of expressive timing, do not constitute a valuable contribution to the field. They only have to be seen in a proper perspective in which their limitations are understood as well. It also does not mean that certain features in computer music software and commercial sequencers should be forbidden. Their mere existence at least makes the realisation of their limited worth evident.

It should be noted here that the views expressed in this article comply more or less with the British school of expressive timing research (E.F. Clarke, H.C. Longuet-Higgins, L. Shaffer, J. Sloboda and N. Todd), in which the link between structure and timing is paramount. There are alternative views developing at the moment, denying such a strong link (Kendall & Carterette, 1991). We hope this controversy will eventually lead to more understanding of this wonderfully complex aspect of music performance.

In reality the experiments were done using POCO, an environment for analysing, manipulating and generating musical expression (Honing, 1990), which took a bit longer to build than one Christmas.

The holiday was almost over now and we felt that we had not found out many useful things. Our musical friend announced that he would go back to his own piano. He thanked us for the interesting sessions, from which he had learned a lot. But underneath these friendly remarks we could hear the cynicism. He advised us in a fatherly way to get rid of our research papers and start reading biographies of famous composers, in which the true facts about music and its performance could be found. This made the feeling of disappointment even more pronounced. But in a last irrational attack of bravery, we decided not to give in yet and we invited him to come back next Christmas, and to bring his biographies if he wished.

To be continued ...

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