# Musical Microstructure Mirrors Brain Function:
# Durations of Beethoven's and Mozart's Pulse Elements.

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## Abstract

Musical Structure + Microstructure = Music. Three orthogonal principles that largely solve this equation appear to mirror central functions of the human brain and its associated neurophysiology for interpreting music - permitting its reverse engineering: hierarchic pulse, predictive amplitude shaping and organic vibrato. Real time solutions of this equation for particular pieces are means to achieve the composer's or interpreter's intimate, emotionally meaningful concepts, and are not mechanistic. Present and future composers are enabled to specify and hear microstructure for their works, eliminating the second-guessing by the performer on which composers had hitherto depended, a seeming turning point in the history of music. With their algorithmic use, an unexpected finding relating to pulse structure is discovered, that contrary to musicological and notational custom, all of 97 Mozart and Beethoven Allegros have main pulse elements within the hierarchic pulse structure in the range of 200 ms, rather than other choices, the fastest time in which *independently* controllable motor decisions can be carried out by the brain.

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For millennia, music and mathematics have been linked, through 1. pitch ratios, 2. integral time divisions, and 3. harmonics. But notated structural proportions based on these, though necessary, are far from sufficient to describe vital real performance. In living performances the notes have to be supplemented by unnotated and hitherto unnotatable microstructure *(1)* which focuses on the meaning of the music and brings it to life. Composers do think the microstructure, but cannot notate it on paper *(2).* As Leopold Mozart, and C.P.E. Bach *(3)* wrote in their respective classic treatises on needed performance subtleties, it is necessary to lengthen certain notes, to play certain notes louder or softer. But they could not provide quantification - understandably, since this involved timings in milliseconds which no one could either know or follow. Nor could others.

The basic equation is

**structure + microstructure = music**

Except for ritards, musical microstructure in the past has not been linked to mathematics. Added by the interpreter, in part through practice informed by feeling and thought, in part through spontaneous shaping, it in effect fleshes out the dead notes of the score, resuscitating a skeleton kept on ice for hundreds of years - with varied success. Reported here is a solution to the above equation (the ‘problem of music’, for its interpretation) using three mathematical principles, that permits microstructure to be globally designed by the composer or interpreter in a way that is organic to a composition (ie related to structure), and perfected over time *(4)*. Further reported are surprising findings about Beethoven’s and Mozart Allegros resulting from this new theoretical and technological advance, pointing to optimal brain function employment.

Structure given by the score provides pitch height, nominal duration, and nominal loudness for each note. Microstructure emends this. It provides duration deviation, amplitude size, amplitude contour, and vibrato specifically for each note. It has been shown that notes specified in the score carry typically 10 bits of information per note. However, needed microstructure adds 17 bits more of information per note, even without vibrato, expressive intonation, or special timbre effects *(5)*. The heart of the problem is that small changes in microstructure can cause very substantial changes in musical meaning *(6, 24 p53-7)*.

Tackling the problem is facilitated by the double stream theory of music *(6),* according to which hypothesis, in music the pulse constitutes one stream S1, and the developing ‘story’ of the music is another stream S2, and both streams are simultaneously processed by the brain. S1, the ‘gait’, is repetitive, with automatism once begun; but capable of modulation in tempo. Once begun it carries through as a mental stream substantially unchanged in gait character, through rests, unmodified by dynamics (overall loudness or softness) with breaks only at quite major sections of the music.

Stream S2 is varied and developing, and has clear subsections with beginnings, middles and ends, called phrases *(7).* When phrases (or shorter motivs) repeat or are varied, the differences, even when small, carry particular meaning, and are perceived in short term and working memory.

Relevant to S1 is Timeform Printing *(8, 6),* a readily performed motor control ability of the brain, which allows the central nervous system to maintain an initially programmed movement pattern with little attention, through continuing repetitions (eg a circular, elliptic, to and fro, triangular or more complex movement of the arm, say at a tempo of Metronome Mark [MM] 70-80 per minute) - until a brief modifying command requiring momentary attention is given by the brain, which then changes (preprograms) the movement to a different repeated pattern, or stops it. The repetitive pulse in music is considered an internalization of such automated movement: an internal time-form printing.*(8, 6).*

Brain function studies which compare imagined movements to actual movements have pointed out salient similarities of specific activation patterns *( 9).* Recent studies with fMRI and PET imaging show evidence that imagined repeated movement has clear brain functional correlates in activating Brodmann areas 6 and 7, the Supplementary Motor Area, and the preSupplementary Motor Areas, which it shares with actual movement, while largely not involving the primary motor area of the brain *(10).* It appears also that repetitive movements activate different brain areas than single movements, in particular the dorsolateral and medial premotor regions *(11).* Such studies are becoming the ground work for understanding S1 brain processing. They are also a step towards understanding aspects of how a composer who became deaf (Beethoven) could compose music of greater subtlety than when able to hear.

On the other hand, other studies are beginning to elucidate the different brain processing of S2 in which melodic notes rather than repetitive pulse components involve motor and auditory imagining, and many regions of the brain are involved *(12).*

In the work reported here, microstructure is created from structure using the software program SuperConductor that models the three mathematical principles, and which avoids musical pitfalls of MIDI (notably, lack of individual note shaping and individual note vibrato, and inadequate amplitude resolution). Under the musical guidance of the interpreter or composer, it creates a documented microscore (permitting anyone to repeat the results, an indispensable scientific requirement) and performs the music on a standard PC *(13), (14).*

Musical microstructure offers a rich opportunity to study temporal acuities of seemingly different clocks in the brain. *(6),(15),(16).* A large portion of time microstructure related to meaning lies in small differences between short tones of fractional seconds' duration. The time differences, in the millisecond range, tend to be linked to substantial amplitude differences among these same notes forming combined gestalts *(17).*

In addition, varied amplitude contour *shapes* of individual notes can help substantially to define meaning - to embody the musical thought of the composer, and its emotional nuances (hence the acknowledged superiority of instruments such as violins, cellos, or the human voice, that can provide these *(18).*

The first of three principles that permit the global design of organic microstructure (global refers to not needing to design the specific microstrucure of each individual note manually) is the Hierarchic Pulse, carried by S1. It consists of a *combined amplitude and time warp (19)* for a specific composer. This grid affects the amplitude sizes and durations of all notes. It describes systematic modifications in relative durations and amplitudes (loudnesses) within a group of four nominally even time slots, whether or not there are notes occupying these slots. Its basic form for a four-pulse is a matrix

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | a1, | a2, | a3 | for Mozart this is | 1 | .32 | .64 | .35 | for Beethoven | 1 | .35 | .75 | .74 |
| t1 | t2 | t3 | t4 | | 107 | 94 | 105 | 94 | | 106 | 89 | 96 | 111 |

for a four element pulse *(6)* and has six degrees of freedom *(20)*
(amplitudes, top row, are in linear units and time, bottom row, is normalized so that 100 represents evenness).

Significantly, the warp pattern, involving all instruments, appears hierarchically on several levels of temporal organization but with different degrees of prominence. The warp of one level is projected onto the level below it, for both durations and amplitudes. It is a metarhythm on which the specific rhythms of the piece are played out. The duration of a note or a rest is the duration of the pulse components it occupies; the amplitude of a note is that of the first pulse component it occupies. (The validity of this composer-specific warp has been tested and proved with interchanged pulses of four composers and proved with 125 subjects of varying musical attainments - from non musicians to foremost musical artists - REF…….)

One needs, however, to find the appropriate *levels of hierarchical organization* for a particular piece, called the *pulse configuration (21).* This categorical choice is not provided by the score. RIGHT OR WRONG Configuration.

In the interpretation and performance of more than 100 Mozart and Beethoven Allegros of larger works *(22)* in duple time with SuperConductor, which includes the algorithmic embodiment of the above three principles, it was found that they all have the hierarchic pulse configuration of (2) * (4, 4) * (4) (low, midlevel, high level). As the 2 shortest notes (low level) are typically notated as sixteenth, the midlevel (main) pulse is in eighth notes, surprisingly, *and not quarter notes*, as might be the straightforward choice dictated by notation and typical written time signature [that would be a configuration of (4) * (4) * (4)] *(23).* This finding is musicologically of considerable significance (and facilitates the interpretation of their other works).

It is understandable that if an allegro piece is notated in 4/4 time (four quarter notes per bar) that a quarter note be given a primary attention. However the findings here indicate that the main level pulse structure in all these works is not four quarter notes, but four eighth notes.These four eighth notes are carriers of the composer's pulse signature, a 4-group of combined amplitude and timing warps.

Moreover, the midlevel pulse of the hierarchy consist of 2 groups of four eighth notes; the second group tends to be of about 14% greater amplitude than the first in Beethoven, and 17% smaller in Mozart (Fig. 1).

Mean Beethoven and Mozart tempi for the Allegros were

137.1 MM, with s. d. across pieces of 18.9 for Beethoven,

140.2 MM and s. d. 16.4 for Mozart.

The mean times across *pieces* for eighth notes are

219 ms ± 29ms s. d for Beethoven

214 ms ± 16ms s. d. for Mozart

(By comparison, the unsuited notation-connoted choice of quarter notes is in the 400 ms range)

Consider now that in the study of brain function, the interval of approximately 0.17-0.2 seconds which had been termed the "present moment" by this author *(24)* has special significance. It is the shortest time to carry out a new motor decision *(25)* (under non emergency situations), the time for individual finger taps when subjects tap repetitively as fast as they can *(26),* reaction time *(27),* and the typical duration of syllables in speech *(28).*

A further surprising finding, therefore, turns out to be that these eighth notes fall into the time ambit of .2 seconds. Since the pulse is programmed by the brain, it appears most efficient that the four allegro *main-pulse elements* should be close to fastest individually controllable *(29).*

For the comprehensive study of microstructure, most of the works necessarily involve music for strings and other instruments capable of individual note shaping. For such instruments and the human voice, the second principle, Predictive Amplitude Shaping (PAS) designs individual but globally controlled shapes for each note, related to musical structure and so in that sense organic.

PAS does this by using Beta Functions *(30).* They are defined as:

$$x^{p_1}(1-x)^{p_2} \quad for \;\; 0 \;\leq\; x \;\leq\; 1$$ normalized to unity maximum amplitude

by $$N = \frac{p_1^{\,p_1} p_2^{\,p_2}}{\left(p_1 + p_2\right)^{(p_1+p_2)}}$$

giving an amplitude envelope shape as a function of time t, (0 < t < T)

$$A(t) = \frac{G}{N}\left(\frac{t}{T}\right)^{p_1} * \left(1-\frac{t}{T}\right)^{p_2}$$ for a note of duration T and amplitude G.

They are a wide family of curves specified by only two parameters $p_1$ and $p_2$, $\left(p_1,\, p_2 \geq 0\right)$ which encompasses the shapes of notes encountered. A basic shape is chosen for a particular voice ( $p_{i1}$, $p_{i2}$ ) and placed on each note, and is skewed forward or backward on the note depending on the slope of the pitch time curve from the present note to the next note. The shape of each note is given by $$p_1 = p_{i1}e^{bs\exp(-aT)}, \quad p_2 = p_{i2}e^{-bs\exp(-aT)}$$

where s = the number of semitones to the next note, T is the duration of the present tone in milliseconds, a and b are constants relating to duration and pitch respectively (.00269 $ms^{-1}$ and .20 $semitone^{-1}$) *(31).*

The modified shape implicitly predicts what is to follow, somewhat how in speech the form of a syllable predicts how the next syllable might be formed. This engenders a sense of continuity, each separate expectation being capable of fulfillment (fig 2).

It turns out that applying Principles 1 and 2 to such music remarkably results in phrasing, that is subtly and globally controllable by the composer or interpreter. Each principle is necessary, and neither alone is sufficient *(32).* That phrasing should arise in this way throughout a piece indicates that the principles represent real brain thought processes.

The third unnotated principle is Organic Vibrato (OV), with equations that describe the specific vibrato amplitude, frequency, rise time, fall time, and differential placement on *each note* of vibrato, where this is used *(33).* Predictive elements are present in these equations also *(34).* The equations combine static and dynamic parameters to design vibrato *differently on each note,* organically {ie directly} related to musical structure (fig. 2). They are also globally controllable for each voice as needed by the music. Detailed equations for vibrato are reserved for a more specialized publication. Vibrato, like the tremor of the human voice, can give added conviction and communicative power, but only when organically applied (that means related to structure, not as overall 'lacquer'). Different pieces of music require different kinds of vibrato.

In addition to microstructure described (a printed out excerpt of the microscore of five violin notes and a rest is shown in fig. 3), music typically has sectional, structural modifications: of tempo, crescendos, and ritards (and their opposites). These mostly notated effects are superimposed multiplicatively on the microstructure *(35, 36)* to achieve the interpretation. There can be some local single note modifications (for example a fermata, or sometimes special accents, affecting typically considerably less than 1% of the notes), and occasional micropauses *(37).*

The vast accumulation of microstructure data generated with SuperConductor (exact specifications at this time of approximately a total of 1,800,000 notes, each note specified by 17 numbers, or 43 bits, with controllable organization) potentiates study of such microstructure data for the first time, on this scale, not through a statistical evaluation, but as aspects of meaningful organization. In this respect it bears resemblance to the study of hieroglyphs, and of code encription. The endpoint of search here is the meaning of the music, and, one may hope, some insights into aspects of the compositional process.

To summarize, it is found that systematic microstructure in the service of the composer's musical thought and meaning makes it possible to design human sounding, feelingful performances *(38)* with real time calculations, that make time into a tool for understanding, as in the physical sciences. In this way, Leopold Mozart's and C.P.E Bach's dream has become reality:

We note that microstructure of music and its principles reflect precise brain processes that help us to a better understanding of the language of music, and in some measure, of the brain itself. The ability to independently and controllably vary stream 1 and stream 2 microstructure now presents new opportunities for further study of music and brain function. The findings on hierarchic pulse structure of Beethoven and Mozart allegros are an initial step towards this.

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**References and Notes**

1. M. Clynes, in *Studies in Music Performance, vol. 39, Publications of the Royal Swedish Academy of Music,* 76 (1983)

2. In Western music. Music of other cultures, for example Indian, largely avoids this dichotomy, as well as the immortalization of specific composers, by not notating specific note details at all.

3. Leopold Mozart, *Versuch einer gruendlichen Violinschule,* Augsburg, J.J.Lotter (1756).
C.P.E. Bach, *Versuch ueber die wahre Art das Clavier zu Spielen*, Berlin, C.S. Henning (1753).

4. Doing so, the listening faculty is exercised to a greater extent than is possible while performing. Spontaneity is channeled through a different route, linked to inner and outer listening, to musical thought apart from motor performance, closer akin to the spontaneity of a painter or sculptor, or, in fact, composer.

5. M. Clynes, *Communication and Cognition, CCAI* **3**, 185 (1986)

6. M. Clynes, *Cognition,* **55**, 269 (1995)

7. Considering the history of music we can observe a shift from predominately S2 in Gregorian chant to predominantly S1 in today's rock music. In the classical era, there was a fine balance between S1 and S2. It appears composers discovered then, without being consciously aware of it, how to make S1 reveal their own identity (presence) [G. Becking, *Der musikalische Rhythmus als Erkenntisquelle*. (Augsburg, Filser, 1928)].

8. M. Clynes and J. Walker, *in Music, Mind and Brain: the Neuropsychology of Music*, *Chap 11,* M. Clynes, Ed (1982 For measurement of invariant gait signatures, see J. N. Carter, M. S. Nixon *Measurement and Control,* **32**, 265 (1999).

9. K. M. Stephan *et al*., *J Neurophys*. **73**,1 373 (1995), M. Jeannerod and J. Decety *Curr. Opin. in Neurobiol*. **5** 727 (1995), M. Jeannerod, *The Cognitive Neuroscience of Action* Cambridge, MA: Oxford (1997)

10. Lepage M. *et al., Cognitive Brain Research* **8** 17, (1999),
S.M. Rao *et al., J. of Neuroscience,* **17,** (14), 5528 (1997).

11. Hollinger P, Beisteiner RT, Lang W, Lindinger G, Berthoz A, *Clin Neurophysiol* **110**, (5) 799 (1999)

12.A.D. Patel and E. Balaban, *Nature* **404**, 80-4, 6773 (2000),
R.J. Zatorre *et al, J Cognit Neurosci* **8** 29, (1996).

13. The program which adjustably incorporates the principles described here, uses straightened samples from which to make the instrumental sounds, individually shaped for each note. It can realistically play symphonies, chamber music or solo works with microstructure, using the A to D converter of the PC or digital sound card. It can record on DAT tape, CDR, or as wav. files on hard disc, in 16 or 20 bits, stereo.

14. Microstructure time resolution is better than 0.5 msec, tempo resolution .05 % and amplitude resolution better than 1 in 10,000. (more details are available on www.SuperConductor.com).

15. D. Epstein, *Shaping Time, Music, the Brain and Performance* N.Y. Schirmer (1994), M. Clynes, *Proc. IEEE Workshop on Robot and Human Communication,* 18, Tokyo, Sept 1992. M. Clynes in K.H. Pribram Ed., *Origins: brain and self organization. Proc. Second Appalachian Conf. on Behav. Neurodynamics* 606, N.J., Erlbaum (1994) In fact, musical meaning augments the perceptual discrimination of small time differences.

16. M. Clynes and J. Walker *Music Perception* **4**, 1, 85 (1986). The total duration of a long piece tends to be conserved across different performances by the same group or individuals who know a piece well, compensating for a slower part with a faster one. Total piece time stability can be as high as 1 part in 500. Tempo discrimination is 1 part in 200. On the other hand differences in the durations of single notes of 200 ms duration or less, for example staccato notes, are perceived as differences between time *chunks* - without separated beginnings, middle and ends - with a resolution of 1-2 ms, clearly involving different brain clock mechanisms.

17. In rests, they are frequently linked to mentally thought amplitude differences, as the musical pulse continues through rests.

18. Shapes contrary to the musical thought that provide sound where there should be none can be especially obnoxious, as they conflict with thinking along with the music: it is easier to think the subtle aspects of a sound shape when not there (eg. to make a piano 'sing') than to ignore a sound that is wrongfully there)

19. That a combined amplitude and time warp specific for a composer is required to produce the pulse was an insight arrived at in 1983 and confirmed across composers and pieces *(6).* Present day PC computers and SuperConductor now allow this to be readily experienced across hundreds of musical works.

20. In pieces in triple time, a corresponding three element pulse has four degrees of freedom.

21. A typical pulse array may be configured as (4 * 4 * 4), (2 * 8 * 4), or (2 * 4 * 4) etc. (low, middle, and high level) and this repeats after 64 elements, 128, or 32 elements, depending on the configuration. all of which have different durations and amplitudes.

22. These include Beethoven: Op 2, No 1, Mvt 1, Op 2,2,1 2,2,4 2,3,1 10,3,1 10, 3,4 13,1 13,3 14,1,1 21,1 21,4 22,1 26,4 27,1,4 31,1 1 31,2,1 36,1 36,4 47,1 53,1 55,4 58,1 59,1 60,4 61,1 67,4 73,1 78,1 92,4 93,4 97,1 101,4 106,1 111,1 125,1 131,3 132,1 133, 135,4 Mozart; K370,1 K453,1 458,4 465,1 467,1 467,2 478,1 488,1 488,3 491,3 493,3, 543,4, 550,1 550,4 551,1 551,4 . Tempi used included Beethoven's original MM mark indications, where available.

23. Configuration of the pulse is categorical: there is only one configuration that clearly fits best.

24.M. Clynes, *Sentics, the Touch of Emotion,* N.Y. Doubleday Anchor, (1977) This corresponds also to experiencing time as a chunk, rather than with an interval with clear beginning, middle and end, as does a musical phrase for example *(15).*

25 A. Berthoz, in A. Damasio ed *The neurobiology of decision,* N.Y. Springer, (1995).

26. N. von Steinbuechel, *Experimental Brain Research,* **123** 1-2, 220 (1998), and I.C. McManus, R.I. Kemp and J. Grant, *Cortex* **16**, 331 (1986) report mean values per finger tap in the range of 180-200 ms, with right hand tapping slightly faster than left hand.

27. Sakai K et al, *J Neuroscience* **20** (7) 2691, (2000).

28. T.H. Crystal and A.S. House, *J. Acoust. Soc. Am.* **88,** 1, (1990) report a mean syllable duration of 233 ms and s.d. 48 ms, in 435 English speech runs. W. Ziegler, E. Hartman and P. Hoole, *J. Speech and Hearing Res.* **36**, 683 (1993) found a comparable result in German speech. It is

also the longest time an object may move through the smallest detectable position change and be seen as moving rather than stationary.

29. leaving some margin for even faster prestos.

30. The name Beta Function derives from a similarly named function used in mathematical statistics. It is the argument of integration of the statistician's Beta Function, without the integration. Its use for depicting shapes of tones was suggested by statistitian N. Nettheim in 1982, M..Clynes and N. Nettheim, in *Music Mind and Brain,* M. Clynes ed. Chap 4, N.Y. Plenum (1982)

31. Caps are set for skips greater than a ninth, and notes longer than an adjustable limit duration are treated as textural, sustained notes rather than melodic notes, and are shaped in an appropriately modified manner.

32. Parametrically documented distinction moreover is made possible between merely ‘musical’ results and those that variously express more profound meaning, a matter that is beyond the scope of this article.

33. Vibrato is proportioned into frequency and amplitude vibrato, and the vibrato waveform has a percentage of second harmonic (approx 11%) to provide naturalness, in addition to its rise and fall.

34. A sense of effort is also embodied in these equations: that effort is needed now (towards the end of the note) to reach a higher pitch in the next note, and that some relaxation is possible in going to descend to a lower pitch - a sense derived from singing, the degree of effort modifying the vibrato.

35. Composers vary in the degree that they employ sectional modifications and whether these are introduced to provide contrast and variety (as often in Bach), or whether they are intrinsic to the musical thought (as mostly in Beethoven).

36. Attempts to formalize microstructure were made by J. Sundberg, A. Friberg, and L. Fryden *in Representing Musical Structure* ed. P.Howell, R.West, J. Cross, (1991), who developed a system of 25 rules based mainly on harmony, and applied these rules to short pieces, and to fragments of works. It is not clear how so many rules can be applied in superposition, the more so as each of the rules has a wide range of choice of constants. In their system, in which pulse plays no role ie. S1 is ignored, the same notes would be played the same way regardless whether

they were composed by different composers, contrary to findings already reported by Becking in 1928 *(7)*.

37. Although often considered by laymen as the main contributions to music interpretation, these sectional modifcations are insufficient in the absence of appropriate microstructure.

38.The mathematical control of musical microstructure is in fact a precise gateway to *qualia* of emotion experience. It may well be expected also to help to explore links between time consciousness and consciousness experimentally.

39. Predictive shaping of successive letter shapes in motor execution of handwriting has been studied by Orliaguet, J-P., Kandel, S., Boë, L-J. *Perception,* **26**, 905-912. (1997).

40. I thank Steve Sweet for extensive programming work, A. Patel, J. Walker, B. Repp for comments on the manuscript, and gratefully acknowledge the support of the REC Music Foundation, The Biocybernetic Institute, and past support of CNMAT of UCB, Queen's College University of Melbourne, and The Sydney University, NSW Conservatorium of Music.

**Supplementary material** available, to be posted on the web includes extensive music of Mozart and Beethoven substantiating this work.

# CAPTIONS

Fig. 1a The typical three-level hierarchic pulse configuration is shown here for two works of Mozart and Beethoven. Early, middle and late period works of Beethoven appear to follow this pattern. The duration warp (displayed through the width of the pulse elements) is doubled for better visibility in the midlevel pulse in this illustration. Amplitude relationships are on a linear scale (vertical).. The combined grid is a multiplication of the warp at the three levels (low, middle and high), and this is impressed on the tempo and individual note loudness. A pulse array might be configured as 4 * 4 * 4, or 2 * 8 * 4, or 2 * 4 * 4, 4 * 4 * 2 etc, 64 or even 128 elements each of which are of different duration and amplitude. However, only one organization fits clearly, in these allegros. It is 2 * (4, 4) * 4. The fastest notes (lowest level) usually are sixteenth notes (occasionally notated as eighth notes). The array repeats after its 64 elements (4 bars). The pulse array needs to be occasionally reset for 3 bar phrases or other non 4 bar phrases.

At a tempo of MM 138 say, the eighth note midlevel pulse elements (an established metronome mark step) correspond to

233, 205, 229, 205 ms for Mozart, 231, 194, 209, 242 ms for Beethoven.

At the mean tempi for all Allegro pieces (137.1 and 140.2 respectively), the basic 4-pulse duration pattern is 232, 195, 210, 243 ms for Beethoven,

229, 201, 225, 201 ms for Mozart

To realize the warp at different hierarchic levels, and in different works, attenuation factors $f_A$ and $f_T$ are used, independently for amplitude and for duration, at each level. These change the degree of warp while preserving the warp pattern. The values of $f_T$ and $f_A$ across pieces are:

| | $f_T$ | | $f_A$ | |
|---|---|---|---|---|
| **Midlevel pulse** | | | | |
| Beethoven | 1.047 | s. d 0.090 | 0.956 | s. d 0.142 |
| Mozart | 1.077 | s. d. 0.023 | 1.057 | s. d. 0.147 |
| **High level pulse** | | | | |
| Beethoven | 0.255 | s.d 0.034 | 0.695 | s. d. 0.111 |
| Mozart | 0.268 | s.d. 0.047 | 0.783 | s. d. 0.131 |

indicating that only minor enlargements or reductions of the warp across pieces are called for in the midlevel pulse. The (4, 4) middle level consists of two identical four element groups having a common attenuation factors, differing in group amplitude only.

At the highest level, the duration warp is considerably reduced avoiding fluctuations in tempo which would be noticeable at that level, but interestingly are not sensed as tempo changes at the lower levels.

Fig. 1b. A schematic representation of the hierarchic pulse array for the allegros, extending over four bars.

Fig. 2. Predictive Amplitude Envelope Shaping and Organic Vibrato.

Mozart Quartet K478, Movt 1, Bars 9 and 10, Violin part.

Amplitude envelopes of notes are shaped so as to implicitly presage what may happen next. In this illustration this is best seen in the eighth notes showing the distinctive shapes of each note. All shapes are designed entirely without Mozart's instructions from the score, but use structural information. Continuity and flow derive from satisfactions of fulfilled expectations *(39)* .

Frequency vibrato is shown in the middle trace, and amplitude vibrato (also called tremolo) in the top trace. Organic Vibrato is a combination of frequency and amplitude vibrato. The vibrato also is globally designed taking into account structure, using melodic predictive elements, and is also subject to static influences, such as pitch height, and note amplitude and duration. Notice the differences in the vibrato from note to note

Fig. 3. Microscore, violin part only. The same five notes as in Fig 2.

Mozart Quartet K478, Movt. 1.

The microstructure of each note is defined by ten numbers in addition to its pitch. Length of notes given in nominal sixteenth note units. Amplitudes are on a linear scale. Vibrato depth is given in cents (100 cents = 1 semitone). Vibrato Frequency is in cps. S refers to a slight staccato on the last note of the slur. No intonation changes are made. Pulse entries show onset of high level pulse element. 1 and 2 respectively. The sixth note entry is a rest. A microscore like this can only be executed by a computer, it could not be followed by a human.

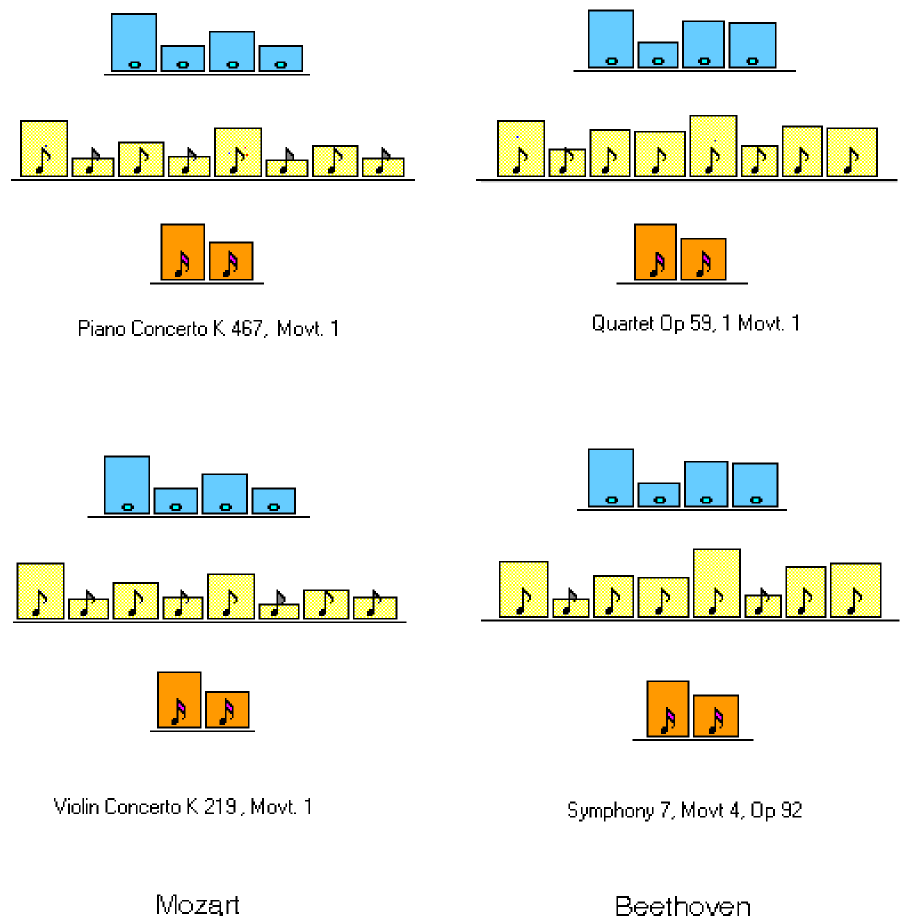


Fig 1a.

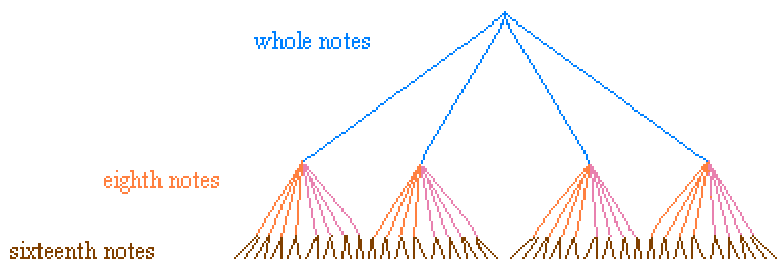


Fig. 1b.

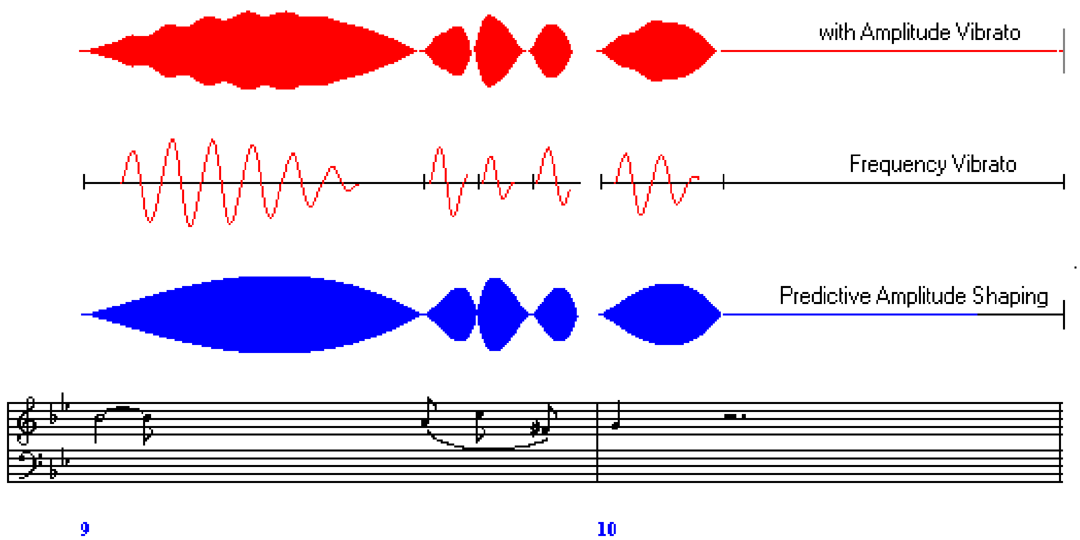
with Amplitude Vibrato
Frequency Vibrato
Predictive Amplitude Shaping
9
10

Fig. 2

| | | | | | Shaping | | | | Vibrato | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pitch | Length | Amp | $P_1$ Rise | $P_2$ Fall | Other | Pulse | Depth | Freq | Rise | Fall | Start | End |
| Bar 9 | 𝅗𝅥♪ | B4♭ | 10.24 | 1037 | 1.27 | 0.96 | | 1 | 9.0 | 7.63 | 0.29 | 0.72 | 0.11 | 0.19 |
| | ♪ | A4 | 1.94 | 462 | 1.61 | 0.75 | | | 8.4 | 7.78 | 0.35 | 0.60 | 0.13 | 0.14 |
| | ♪ | C5 | 2.10 | 699 | 0.82 | 1.48 | | | 5.9 | 7.85 | 0.20 | 1.02 | 0.07 | 0.29 |
| | ♪ | F4# | 1.94 | 464 | 1.28 | 0.95 | S0.27 | | 7.9 | 7.71 | 0.31 | 0.67 | 0.11 | 0.18 |
| Bar 10 | ♩ | G4 | 4.00 | 402 | 1.28 | 0.95 | | 2 | 7.3 | 7.69 | 0.29 | 0.72 | 0.11 | 0.18 |
| | | R | 11.90 | | | | | | | | | | | |

Tempo MM 138.5 per quarternote = 217 ms per nominal eighth note (2 length units)

Fig. 3