Understanding Coarticulation in Music

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Abstract. The term *coarticulation* designates the fusion of small-scale events such as single sounds and single sound-producing actions into larger chunks of sound and body motion, resulting in qualitative new features at the medium-scale level of the chunk. Coarticulation has been extensively studied in linguistics and to a certain extent in other domains of human body motion, but so far not so much in music, so the main aim of this paper is to provide a background for how we can explore coarticulation in music. The contention is that coarticulation in music should be understood as based on a number of physical, biomechanical and cognitive constraints, and that it is an essential shaping factor for several perceptually salient features of music.

Keywords: Coarticulation, chunking, context, music perception, motor control, performance.

1 Introduction

This paper is about how perceptually salient units in musical experience emerge by principles of coarticulation. The term *coarticulation* designates the fusion of small-scale events such as single sounds and single sound-producing actions into phrase level segments, or what we prefer to call *chunks*, very approximately in the 0.5 to 5 seconds duration range. Such fusions into chunks are ubiquitous in music, for instance in the fusion of a rapid succession of tones and finger motion into what we perceive holistically as an ornament, or in the fusion of drum sounds and associated mallets/hand/arm motion into a rhythmical groove pattern.

Although musical experience can be considered continuous in time, it is also clear that what we perceive as salient features of music, e.g. rhythmical and textural patterns, melodic contours, expressive nuances, etc. are all based on holistic perceptions of a certain length of musical sound and music-related body motion: we need to hear and keep in short-term memory a certain stretch of music in order to decide what it is and to assess what are the salient features of this excerpt. This segmenting and evaluation of continuous sensory information we refer to as *chunking*. We use the term 'chunking' because this term not only signifies a segmentation or parsing of continuous sensory streams, but also the transformation to something more solid in our minds, to something that does not exist at the timescale of continuous sensory streams.

As coarticulation is basically about the fusion of smaller elements into larger units, understanding coarticulation may be very useful in understanding chunking in music, and could also be useful for a number of other music-related domains such as music psychology, music theory, and music information retrieval, as well as in advancing our understanding of the relationships between sound and body motion in music, i.e. in research on embodied music cognition [1, 2, 3].

In presenting the main ideas of coarticulation in music, we first need to look at what are the significant timescales at work in musical experience, because coarticulation is mostly a local phenomenon, typically in the 0.5 to 5 seconds duration range. We also need to look at some issues of continuity, discontinuity, and chunking in music, before we go on to the main principles of coarticulation, followed by an overview of ongoing and possible future work in this area.

2 Timescale Considerations

Needless to say, we have musical sound at timescales ranging from the very small to the very large, i.e. from that of single vibrations or spikes lasting less than a millisecond to that of minutes and hours for whole works of music. The point here is that each timescale has distinct perceptual features, and to take this into account, we have in our research postulated three main timescales. An almost identical classification of timescales applies to music-related body motion, however with the significant difference that the maximum speed possible for human motion is of course much less than that typically found in audible vibrations:

- *Micro timescale*, meaning the timescale of audible vibrations, thus including perceptual phenomena such as pitch, loudness, stationary timbre, and also fast but sub-audio rate fluctuations in the sound such as tremolo, trill, and various rapid timbral fluctuations. At this timescale, we typically perceive continuity in both sound and motion, and we keep whatever we perceive in so-called *echoic memory*, forming the basis for the perception of more extended segments of sound and motion at the meso timescale. Interestingly, there also seems to be a limitation on motor control at this timescale by the phenomenon of the so-called *Psychological Refractory Period*, which among other things, suggests that below the (very approximate) 0.5 seconds duration limit, body motion trajectories may run their course without feedback control [4], something that is one of the constraints linked to coarticulation (see section 6 below).
- *Meso timescale*, or what we call the *chunk timescale*, similar in duration to what Pierre Schaeffer and co-workers called the *sonic object* [5, 6], typically in the very approximately 0.5 to 5 seconds duration range. The crucial feature of the meso timescale is the holistic perception of sound and body motion chunks, much due to the fusion effect of coarticulation. As suggested by Schaeffer, meso timescale chunks are probably also the most significant for various salient perceptual features such as the shapes (or envelopes) for pitch, dynamics, timbre, various fluctuations, various rhythmical and textural patterns, something that has been confirmed by listeners' identification of musical features in short fragments [7]. Also other important elements converge in making the meso timescale significant, such as the

assumed limits of short-term memory [8], the average duration of everyday human actions [9], and importantly, theories of the perceptual present [10].

- *Macro timescale*, meaning longer than the typical duration range of the meso timescale, usually consisting of concatenations of meso timescale chunks in succession, and typically extending over whole sections and even whole works of music.

What is essential for coarticulation is that it is found on the meso timescale (but based on continuous, micro timescale elements), and that it concerns both the perception and the sound-producing (and also the sound-accompanying) body motion at this timescale (see [3] for a discussion of sound-related body motion categories). It is in fact the *contextual smearing* of micro timescale elements that is the hallmark of coarticulation in general, and so we claim, also of musical sound and music-related body motion, something that we should first see in relation to notions of continuity and discontinuity in music.

3 Continuity vs. Discontinuity

Western music theory has traditionally regarded the tone (or in cases of non-pitched percussion instruments, the sound event) as the basic ingredient of music, represented by the symbols of Western notation. Although we may think of musical experience as a continuous stream of sound, there is then at the core of Western musical practice a 'discretization' of music into discontinuous tone (or sound) events, represented by notation symbols. This notation paradigm has had as one consequence the concept of music as something that is made by putting notes together, and furthermore, followed by adding some kind of expressivity to these concatenations of notes in performance. One further consequence of this has been a certain abstraction of musical features, including a more 'disembodied' view of music as a phenomenon.

Shifting our perspective to the sound-producing body motions of music, we realize that any musical sound (or group of sounds) is included in some kind of action trajectory, e.g. to play a single tone on a marimba, the mallet/hand has to make a trajectory from the starting (equilibrium) position out towards the impact point on the instrument, followed by a rebound and a trajectory back to the initial position. This means that we have continuity in musical practice in the sense of continuity in sound-producing body motion, but we also have continuity in the resultant musical sound: in spite of a symbolic representation of a tone (or non-pitched sound), it will always have a temporal extension as well as various internal time-dependent features such as its dynamic, pitch and timbre related evolution in the course of the sound, and additionally, very often also be contextually smeared by neighboring sounds. In this sense, we can speak of *temporal coherence* of both sound-producing body motion and the resultant sound, meaning a contextual smearing of that which Western music notation designates by discrete symbols. In the case of Music Information Retrieval, the task is obviously the opposite, i.e. to try to reconstruct the discrete symbolic notation from the continuous stream of contextually smeared musical sound (se e.g. [10]).

This temporal coherence and resultant contextual smearing of both body motion and sound is the very basis for the emergence of coarticulation in music (as well as in language and other domains). What we have then is the emergence of new, somehow meaningful meso timescale chunks, chunks that in turn may be regarded as 'discrete' in the sense that they are holistically perceived (and conceived), i.e. that the continuous streams of sound and motion sensations are cumulatively perceived holistically or 'all-at-once', as chunks, and not primarily as note-level discrete events.

4 Chunking Theories

Attempts to understand chunking have variably looked at features in the sensory input, i.e. in what we could call the *signal*, and for mechanisms in the human mind for segmenting the continuous signal into chunks by the use of various *mental schemas*. We have thus *exogenous* (signal based) and *endogenous* (mental schema based) elements variably at work in chunking in music [12]. As this has consequences for our understanding of coarticulation, we should have a brief look at exogenous and endogenous elements in chunking, noting that in practice there may be an overlap of these two. As for the typically exogenous sources for chunking, we have the following:

- Auditory qualitative discontinuities of various kinds: sound-silence transitions, register changes, timbral changes, etc., partly following experimental findings, partly inspired by classical gestalt theories [13], theories also applied to note level chunking [14]. Although auditory (and notation based) chunking can work well in cases with salient qualitative discontinuities, this becomes problematic when these discontinuities are weak or even non-existent such as in sequences of equal duration and/or equal sounding tones, sequences that most listeners may still subjectively segment into chunks based on various mental schemas (e.g. of meter).
- In human motion research, looking for shifts between motion and stillness as a source for chunking, however with the difficulty that humans (and other living organisms) are never completely still, necessitating some kind of thresholding or other motion signal cues such as peaks of acceleration and/or jerk for finding the start and stop points of action chunks [15]. And as is the case for auditory signals, subjective perception may very well segment streams of body motion into chunks based on various mental schemas, in particular schemas of goal-directed body motion.

Given the various difficulties with purely exogenous sources of chunking, there has been a long-standing and extensive effort in the cognitive sciences to search for more endogenous sources for chunking. This was a central topic in phenomenological philosophy at the end of the 19th century, in particular for Edmund Husserl with his idea that experience spontaneously proceeds by a series of chunks that each contain a cumulative image of the recent past, the present moment, and also of future expectations [16, 17]. The inclusion of future expectations in Husserl's model is quite remarkable in view of recent theories of motor control, i.e. that at any point in time, we are not only having the effects of the recent past motion, but just as well preparing the coming motion. This inclusion of the recent past and the near future in chunking is one of the hallmarks of coarticulation in the form of so-called *carryover* and *anticipatory* effects. Additionally, there are some more recent research findings on endogenous elements in chunking that we have found useful for understanding coarticulation:

- *Goal-directed motion* [18], meaning that human motion is planned and controlled in view of arriving at certain goal postures, what we in our context have chosen to call *goal points* so as to signify the effector (i.e. fingers, hands, arms, torso, vocal apparatus) postures and positions at certain salient points in time such as downbeats and other accents in the music.
- *Action hierarchies* [19], also suggesting that human motion is controlled by goals and that sub-motions are recruited as needed, and importantly, are then fused by coarticulation.
- *Action gestalts* [20], documenting that human motion is pre-planned as holistic chunks.
- *Intermittent control* [21], suggesting that continuous control of human motion is neither well documented nor would be particularly effective as there would invariably be delays in any feedback system, hence that a more discontinuous, 'point-by-point' or 'chunk-by-chunk' kind of motor control scheme would be more efficient.
- *Psychological Refractory Period* mentioned above [4], suggesting that there is a minimal duration for intervening in motor control, hence yet another indication that motor control proceeds in a chunk-by-chunk manner.

Chunking in perception and cognition could be summarized as the cutting up of continuous streams into somehow meaningful units and the transformation of the sequential to the simultaneous in our minds. All the details of how this works seems not yet to be well understood, however chunking seems to be based on a combination of exogenous and endogenous elements. This is actually one of the main points of the so-called motor theory of perception [22], namely that we perceive sound largely also with the help of mental images of how we believe the sound is produced, and it seems that this also applies to the perception of coarticulation.

5 Principles of Coarticulation

Coarticulation, understood as the fusion of smaller events into larger scale chunks, is a general feature of most human (and animal) body motion, and can be understood as a 'natural' or emergent phenomenon given various biomechanical and cognitive constraints of the organism (as well as some physical constraints of musical instruments and even room acoustics). Given these various constraints, coarticulation concerns not only the production of body motion and sound, but also the features of the sensory output, and the perception of these features, as has been extensively studied in linguistics [23].

Basically, coarticulation can be seen in a broader context as an advantageous element: "…it is a blessing for us as behaving organisms. Think about a typist who could move only one finger at a time. Lacking the capacity for finger coarticulation, the person's typing speed would be very slow. Simultaneous movements of the fingers allow for rapid responding, just as concurrent movements of the tongue, lips and velum allow for rapid speech. Coarticulation is an effective method for increasing response speed given that individual effectors (body parts used for movement) may move relatively slowly." ([24]: 15). Thus, coarticulation concerns both temporal unfolding of motion and the degree of effector activation in motion:

- *Temporal coarticulation*: otherwise singular events embedded in a context, meaning that past events influence present events, i.e. position and shape of effectors are determined by recent action, by *spillover* or *carryover* effects. But also future events influence present events, i.e. the positions and shapes of effectors are determined by the preparations for future actions, showing *anticipatory* effects.
- *Spatial coarticulation*: motion in one effector (e.g. hand) recruits motion in other effectors (e.g. arm, shoulder, torso).
- Coarticulation seems to be a biomechanical necessity, i.e. is based on constraints of our bodies' capacity to move.
- Coarticulation seems to be a motor control necessity, i.e. is based on our need for anticipatory programing of motion in order to be fast and efficient.
- Coarticulation results in contextual smearing of the perceptual output, i.e. of both sound and body motion.

As to the last point, we could speculate that there has been an evolutionary 'attunement' of production and perception here in the sense that various linguistic, musical, and other expressions are based on the combined biomechanical and motor control constraints that lead to coarticulation, and that the ensuing perceptions of these expressions are well adapted to coarticulation, i.e. that our perceptual system actually expects coarticulation to take place.

6 Constraint Based Coarticulation

Coarticulation can be understood as an emergent phenomenon, given various constraints of the human body and our cognitive apparatus, but also of musical instruments and even of room acoustics:

- Sound-producing actions, both instrumental and vocal, include (variably so) a preparatory motion phase, e.g. positioning of the effector such as the bow above the strings on a violin ready for a down stroke, or the shaping of the vocal apparatus and inhaling before a voice onset, etc.
- Body motion takes time: needless to say, there are speed limitations on all kinds of body motion meaning that there is always a travel time for an effector from one position or shape to another position or shape, implying in turn that there is a contextual smearing by continuous body motion between the temporally more discrete postures.
- Another feature related to speed limitations is the emergence of changes known as *phase transition* [25], meaning a switch to a different grouping and/or motion pattern due to change in speed, e.g. as the transition from walking to running. This can be observed in music as a transitions from discrete motion to more continuous motion e.g. in tremolo as can be seen in Figure 1. To what extent such phase transitions are due to biomechanical or motor control constraints is not clear, but once the threshold from discrete individual hitting motion to continuous oscillating motion is crossed, we do in fact have a constraint based case of coarticulatory fusion.

- Control theory has often distinguished between so-called *open loop* (meaning no feedback) and *closed loop* (meaning having feedback) control schemes, both in machine control and in human motor control. The dominant view has been that closed loop is at work in human motor control, however, one problem with this view is that feedback control takes time and thus cannot be continuous, and rather has to be intermittent as suggested by the abovementioned theories of the Psychological Refractory Period. This would result in motion trajectories that, once initiated, run their course, fusing all micro motions within such trajectories by coarticulation.
- Lastly, we also have the physical phenomenon of incomplete damping, both in instruments and in rooms, meaning that there is a contextual smearing due to reverberation in the source as well as in the rooms where the musical performances take place. Coarticulation is then actually also related to the physics of energy dissipation, and not just regarding rate of damping in instruments and rooms, but also in body motion, e.g. as in the rebound of mallets in percussion performance.

In a sense, coarticulation is an attempt to live with, or even exploit, these various constraints, for the purpose of human expression, including music: besides coarticulation as a result of constraints, we of course also have volitional, or intended, coarticulation, meaning that musicians have the capacity to produce expressive musical sound *with* these features of coarticulation.

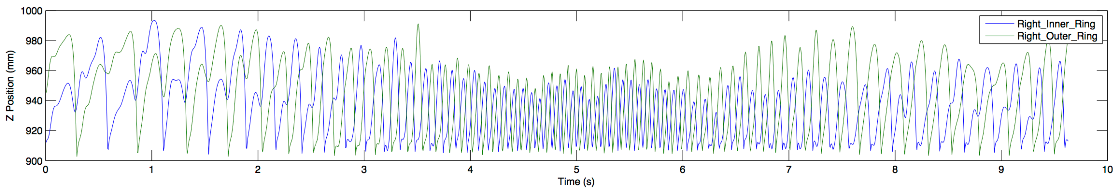

Figure 1. The motion trajectories of two mallets held by the right hand alternating between two tones, E4 and C5, on a marimba, initially slow, then accelerating to a fast tremolo and then decelerating back to slow alternations. Notice the bumps due to the recoil for slow motions, their disappearance with acceleration, and reappearance with deceleration, signifying a phase transition from discrete to continuous and back to discrete motions as a function of speed[1].

7 Coarticulation in Practice

Although coarticulation has been most extensively studied in linguistics and partly also in other domains concerned with human body motion, there have been some studies of coarticulation and/or coarticulation related phenomena in music:

- In piano playing: fingers move to optimal position before hitting keys [26].
- In string playing: left hand fingers in place in position well before playing of tones [27] and contextual smearing of bowing movements [28].
- In drumming, a drummer may in some cases start to prepare an accented stoke several strokes in advance [29].

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[1] The plotting in this figure and figures 2, 3, and 4 are all based on marker data from a Qualisys infrared camera system recording the musicians' body motion at 100Hz.

- In trumpet performance, there are different articulations that (variably so) exhibit coarticulation between successive tones [30].

In our own research, we are presently studying coarticulation in performance on string instruments, as well as percussion instruments and piano. Coarticulation is perhaps most eminently present in non-keyboard instruments as these allow more control over articulatory details, and we are planning to move on to studying coarticulation in woodwind and brass instruments, and later on also in singing. Although coarticulation in the human vocal apparatus has probably been the most studied field of coarticulation [23], we envisage several challenges of correlating sound features and production features in singing.

We have in our own previous work on coarticulation focused on hand-wrist-elbow motion in piano performance (see [31] for details), but more recently focused on shorter passages and ornaments in piano, percussion and violin performance, in view of ornaments as prime cases of coarticulation by the constraints of high speed and assumed need for anticipatory motor control (as well as the resultant smearing of sound and motion). In Figure 2, we see the motion of the five fingers of the right hand embedded in the motion of the hand, wrist and elbow.

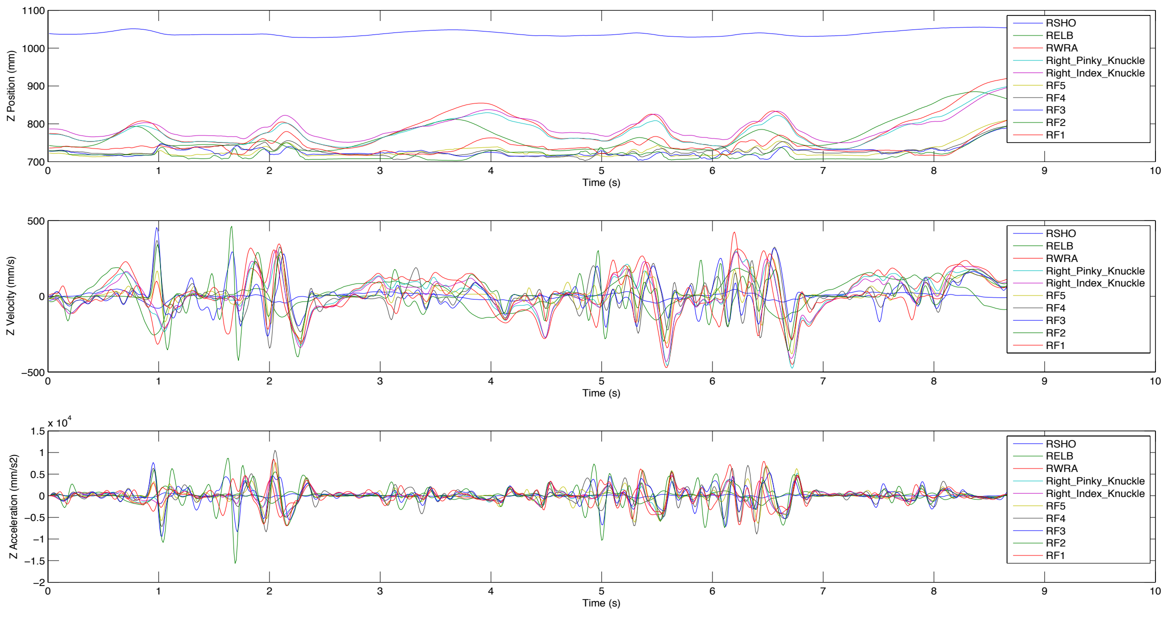

Figure 2. The right hand fingers, knuckles, wrist, elbow and shoulder motions in performing the ornaments form the opening of the second movement of W. A. Mozart's Piano Sonata KV 332, the three graphs showing position (top), velocity (middle) and acceleration (bottom). Notice in particular the motion of the knuckles, wrist and elbow in relation to the finger motions, demonstrating both temporal and spatial coarticulation.

We have also studied coarticulation as motion trajectories to and from goal points, what we have called *prefix* and *suffix* trajectories to goal points (see [12] for more on goal points). An example of this can be seen in Figure 3 where there is a rapid, burst like cascade of tones leading up to the goal point of the Bb5, and with the marimba player's right hand continuing after hitting this Bb5 with a 'follow through' motion similar to what can be seen e.g. in golf or tennis.

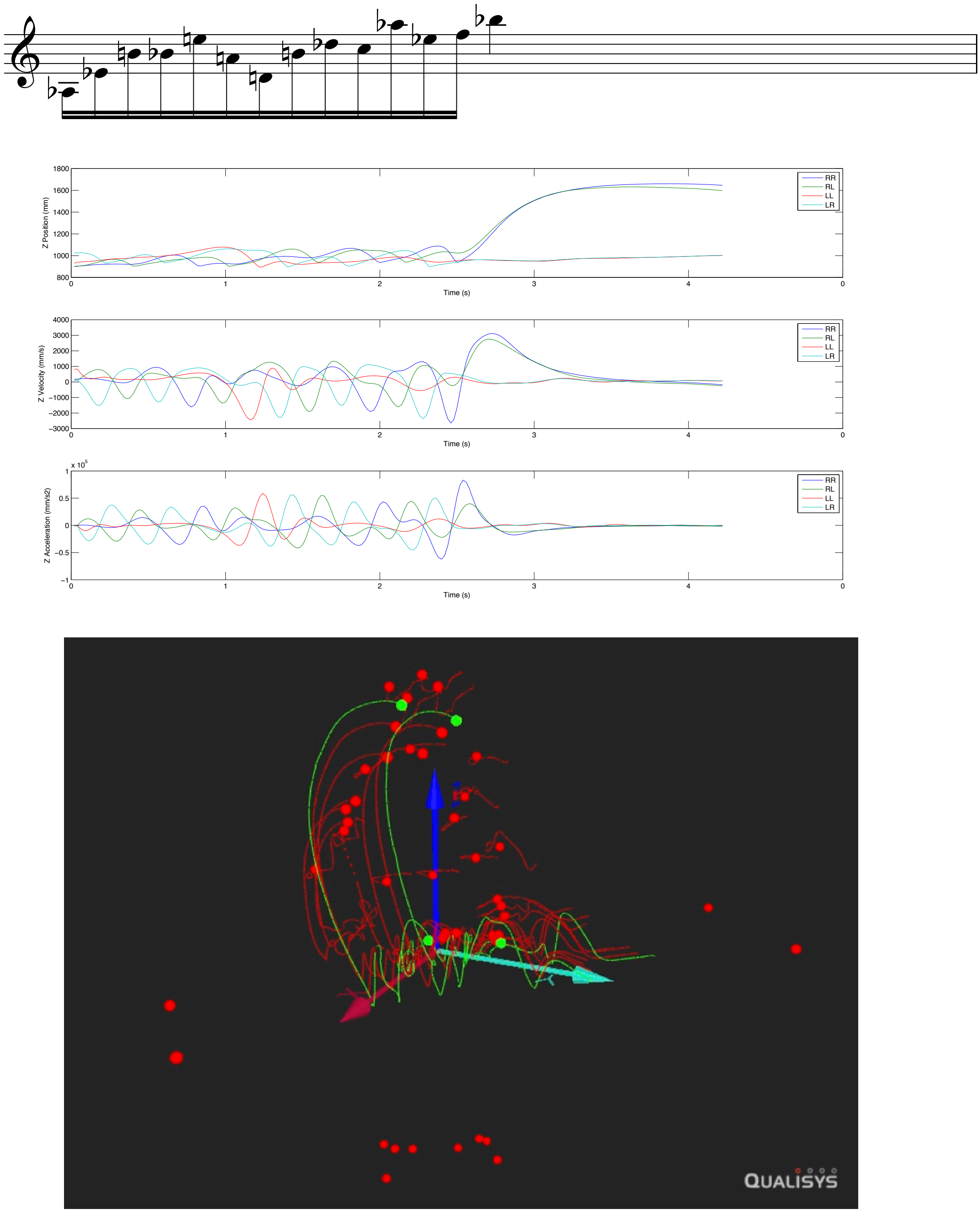

Figure 3. The marimba performance with four mallets of a rapid prefix trajectory leading up to the goal point of the Bb5. The position, velocity and acceleration of the four mallets are displayed below the notation of this passage, and at the bottom of the figure we see a 'cumulative' trajectory picture of the mallets' and whole body of the performer by the markers' 'tails'.

We hypothesize that the focus on goal points in coarticulation may be related both to the abovementioned Psychological Refractory Period [4] and to findings on 'intermittent control' of body motion [21], suggesting a more 'point-by-point', rather than a continuous feedback, scheme in motor control. The idea of intermittent control is not new (although the labeling may be new), and the debate on continuous vs. intermittent control has in fact been going on for more than 100 years [18, 32]. As a further example of such intermittent, 'point-by-point' organized body motion (sometimes referred to as *ballistic motion*), consider the excerpt in Figure 4 of the first couple of measures of the last movement of Beethoven's *Piano Concerto No. 1*. Here we can see such a 'point-by-point' coarticulatory subsumption of the detail motions and rhythmic articulation to the downbeat points.

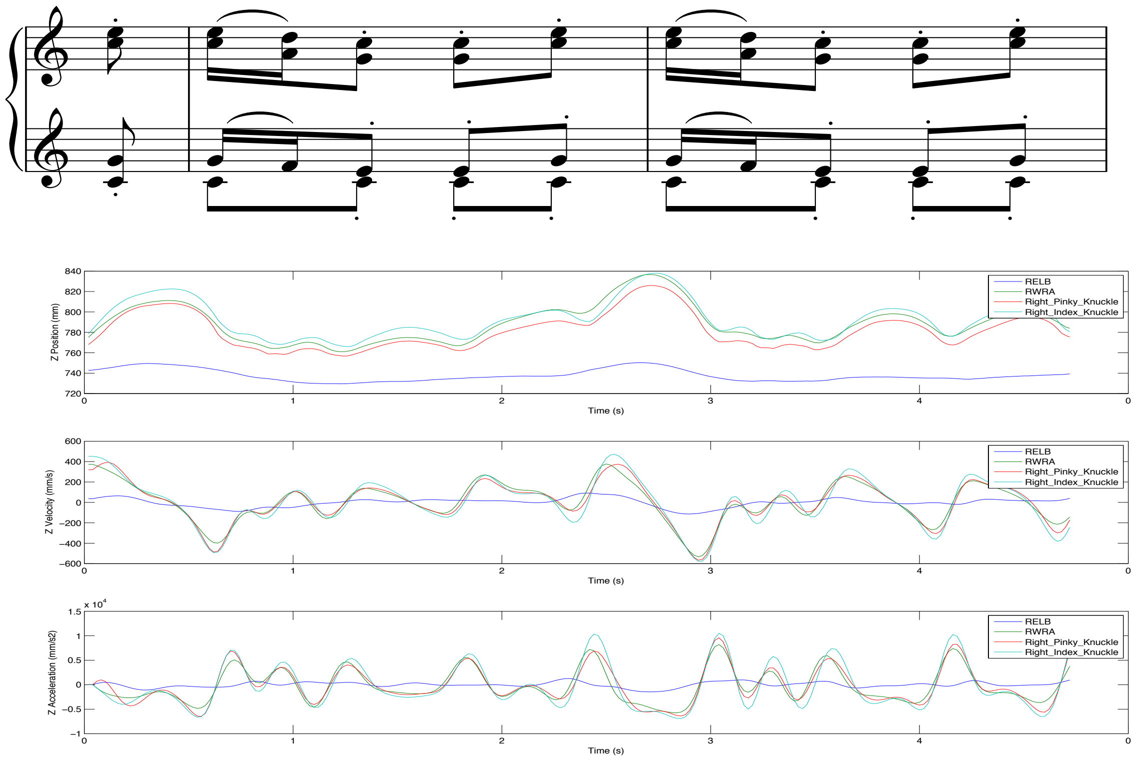

Figure 4. The graphs show the position, velocity and acceleration of the vertical motion of the right hand knuckles, wrist and elbow in the performance of the two first measures of the third movement of Beethoven's *Piano Concerto No. 1*. Besides the up-down motion around the downbeat points, also notice the relative high velocity at these points, typical of so-called *ballistic* motion.

As suggest in [33], and previously inspired by some models of coarticulation in linguistics [34], the phenomenon of intermittent control by goal points could be schematically illustrated as in Figure 5. This illustration shows first a singular goal point, the trajectory to and from this goal point (i.e. its prefix and suffix), then a series of goal points and their corresponding to and from trajectories. In the latter case, with the overlapping prefix and suffix trajectories, the result is actually a more undulating motion curve, appearing to be continuous in spite of the singular goal points being intermittent. In more general terms, this resembles the relation between an impulse and the impulse response of a system, something we are now developing further [33].

The basis for coarticulation is then that there are continuous motion trajectories, effectively creating continuity and coherence in the perceived sound and body motion, however the control of these continuous trajectories may be based on discontinuous impulses. One interesting aspect of coarticulation is then that it could be a supplement to more traditional bottom-up, signal based modeling of gestalt coherence. The saying that 'the whole is more than the sum of the parts' often encountered in connection with gestalt theory, acquires a new meaning when we take the coarticulatory contextual smearing into account: coarticulation is actually a transformation of the parts into something new, so yes, the whole is more than a sum of the parts. In this perspective, most musical features can be considered in view of being coarticulated gestalts: melodic, rhythmic, textural, metrical, etc. patterns could all be seen to owe their coherence to coarticulatory contextual smearing.

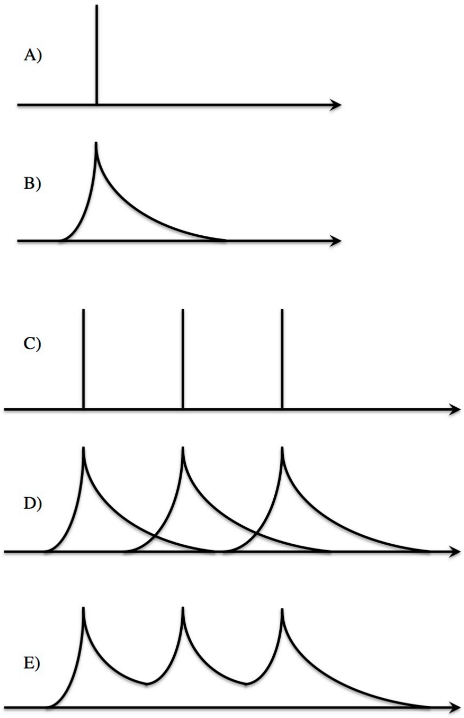

Figure 5. A schematic illustration of continuous motion in relation to goal points. If we consider a goal point, A), positioned along the temporal axis, it takes time to travel to and from that goal point, resulting in a trajectory as in B). When we have several goal points in succession as in C), we also have several to and from trajectories in succession as in D). If these to and from trajectories overlap, we end up with apparently continuous, but undulating, trajectories like in E). Illustration borrowed from [33].

8 Summary and Further Work

Coarticulation, understood as the fusion of small-scale events into more superordinate chunks, clearly seems to be at work in music. Furthermore, in making a survey of various physical, biomechanical, and motor control constraints involved in sound-producing actions, it seems that coarticulation is an emergent phenomenon from these constraints. Additionally, it could be speculated that our perceptual apparatus is so attuned to coarticulation that without coarticulation, music would sound 'unnatural', something which is often the opinion of people listening to sampled instruments that are not capable of coarticulation as acoustic instruments are.

In relation to our Western musical concepts of discretized tones and notation, coarticulation may appear as something 'added' to the notes in performance. Yet, as is the case for coarticulation in language, this is turning things on the head, in forgetting that discretization into units both in music (pitches, durations) and in language (phonemes, syllables) are probably secondary to more primordial musical and speech practices where coarticulation would be intrinsic.

One task in future research will thus also be to take a critical look at notions of continuity and discontinuity in Western musical thought, in view of recognizing the continuous body motion and resultant contextual smearing as not something added to music, but as something intrinsic to music as a phenomenon. Needless to say, there are also substantial challenges of method, of finding out more in detail of what goes on in sound-producing body motion as well as the many details of coarticulation in perceived sound and body motion. Fortunately, we now have the methods (including the technologies) to explore the details of such real-life contextual smearing in music, and thus we can hopefully contribute to our understanding of music as a phenomenon.

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