Motion-Sound and Sound-Motion Analysis

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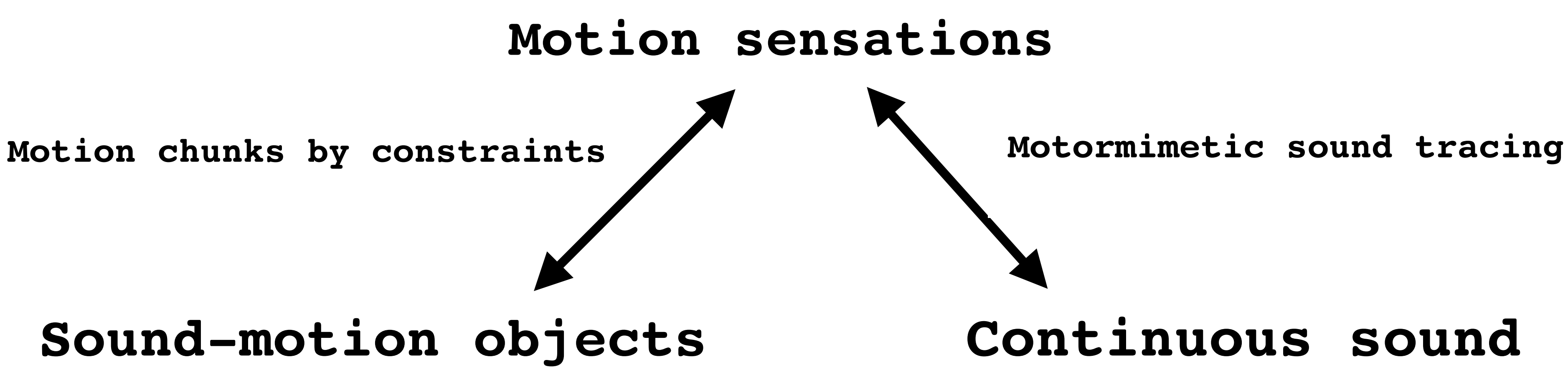
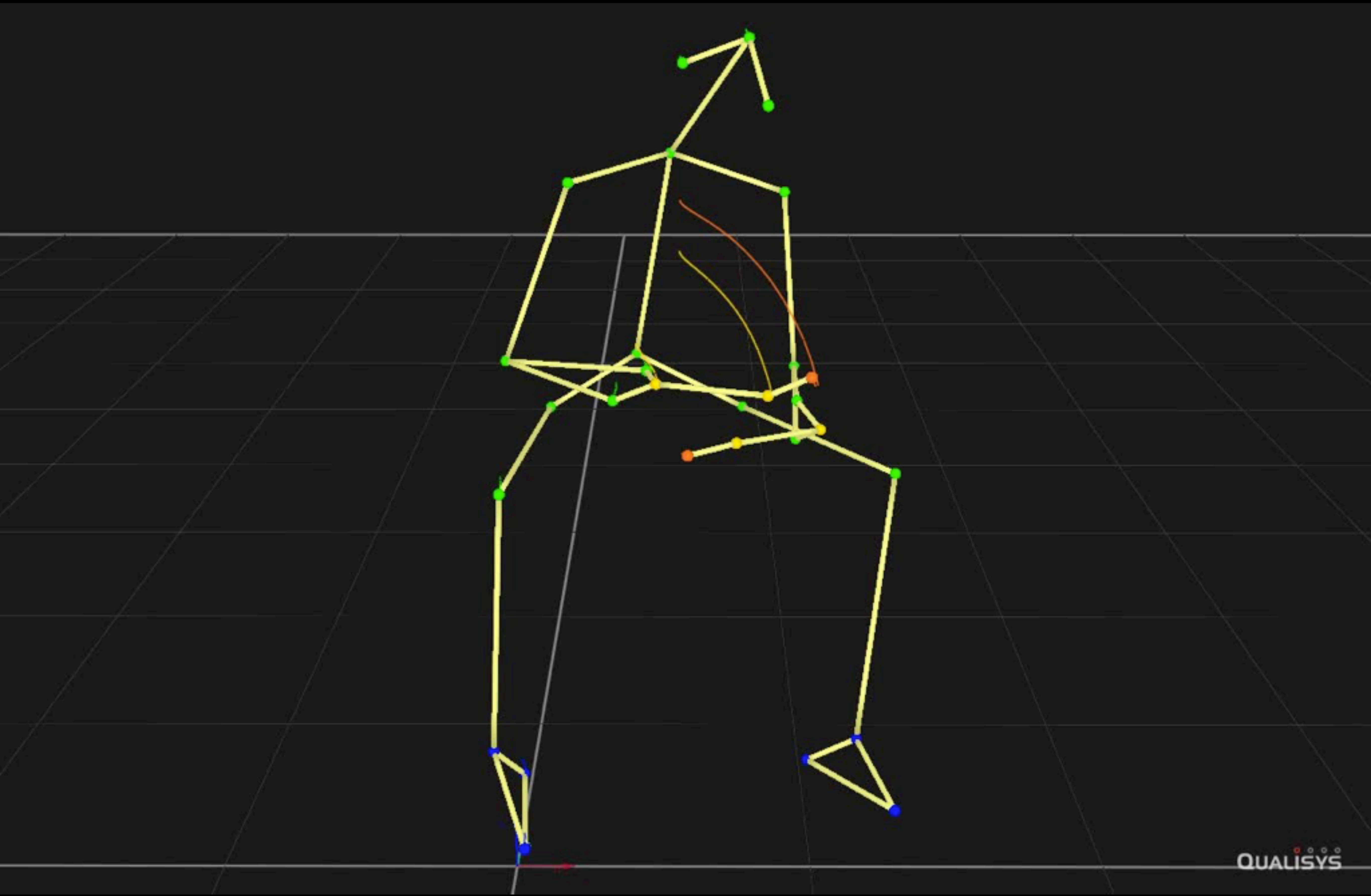
Main ideas of sound-motion analysis:

- Music may be considered to consist of a series of multimodal chunks, what we call *sound-motion objects*, each comprising sensations of sound and sound-producing body motion, by what we call *motormimetic cognition*:



- Crucial *constraints* on sound-producing body motion
- See how the sound is included in the sound-producing body motion shapes for this drum set excerpt:



Main claims of sound-motion analysis:

- We seem to perceive a stream of sound and body motion centred on highly accented points in time, with these points surrounded by what may be called *prefixes* and *suffixes*
- The accented points are produced by *ballistic motion*, in turn the result of *open loop* (discontinuous) impulses
- We hypothesise that these sound-motion objects are the result of *intermittent motor control* and *intermittent effort*, i.e. that there is an unequal distribution of attention and effort in the course of musical performance, and that this also affects perception
- Also, notice the *bimanual* and *biped* coordination from an "egocentric" perspective

Motormimetic cognition:

- *Motormimetic cognition* = mental images of body motion
- Inspired by the so-called *motor theory of perception* in linguistics, but now also extended to other domains
- Covert imitation of the motion of others and/or the assumed motion behind what we hear
- Human movement involved in most perception and cognition, e.g. Berthoz (1997):

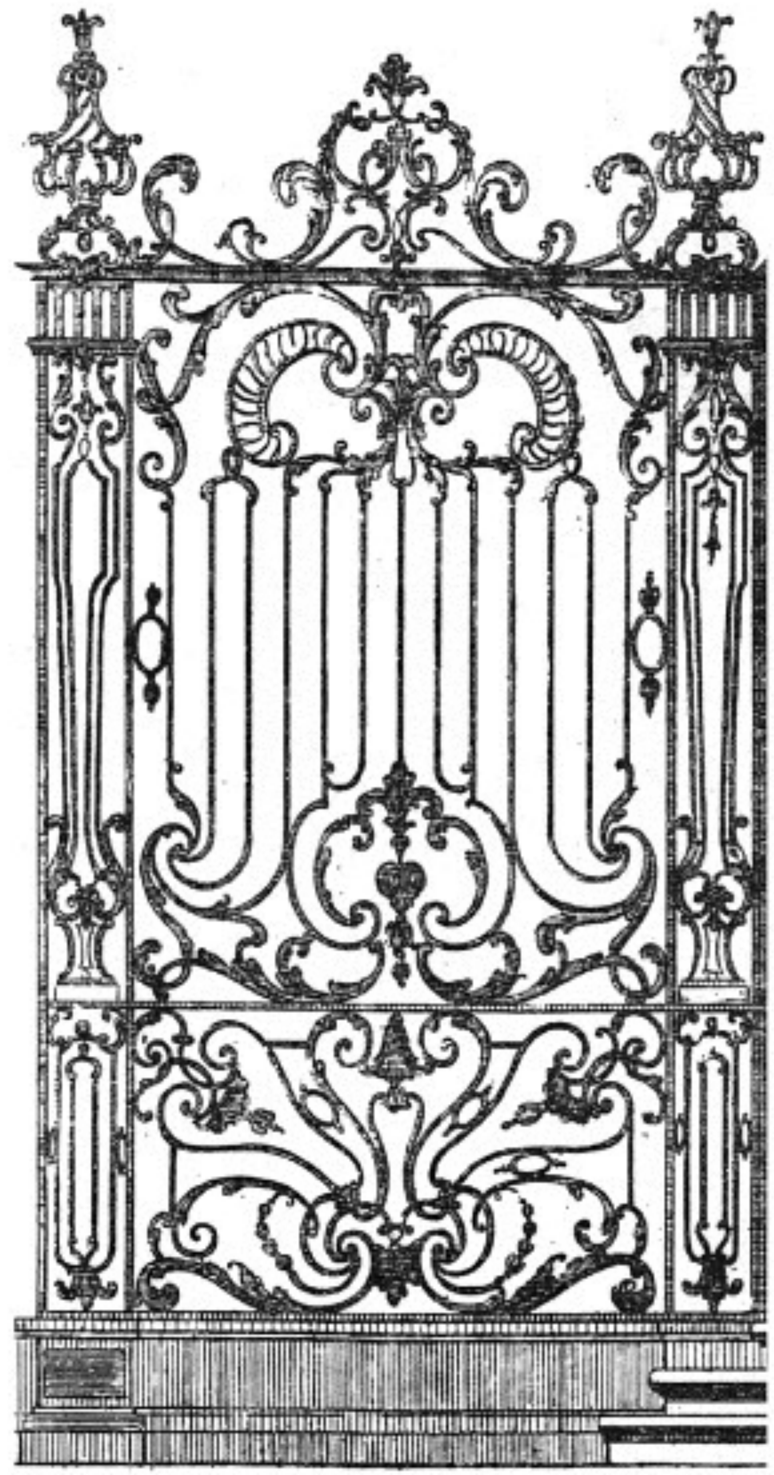


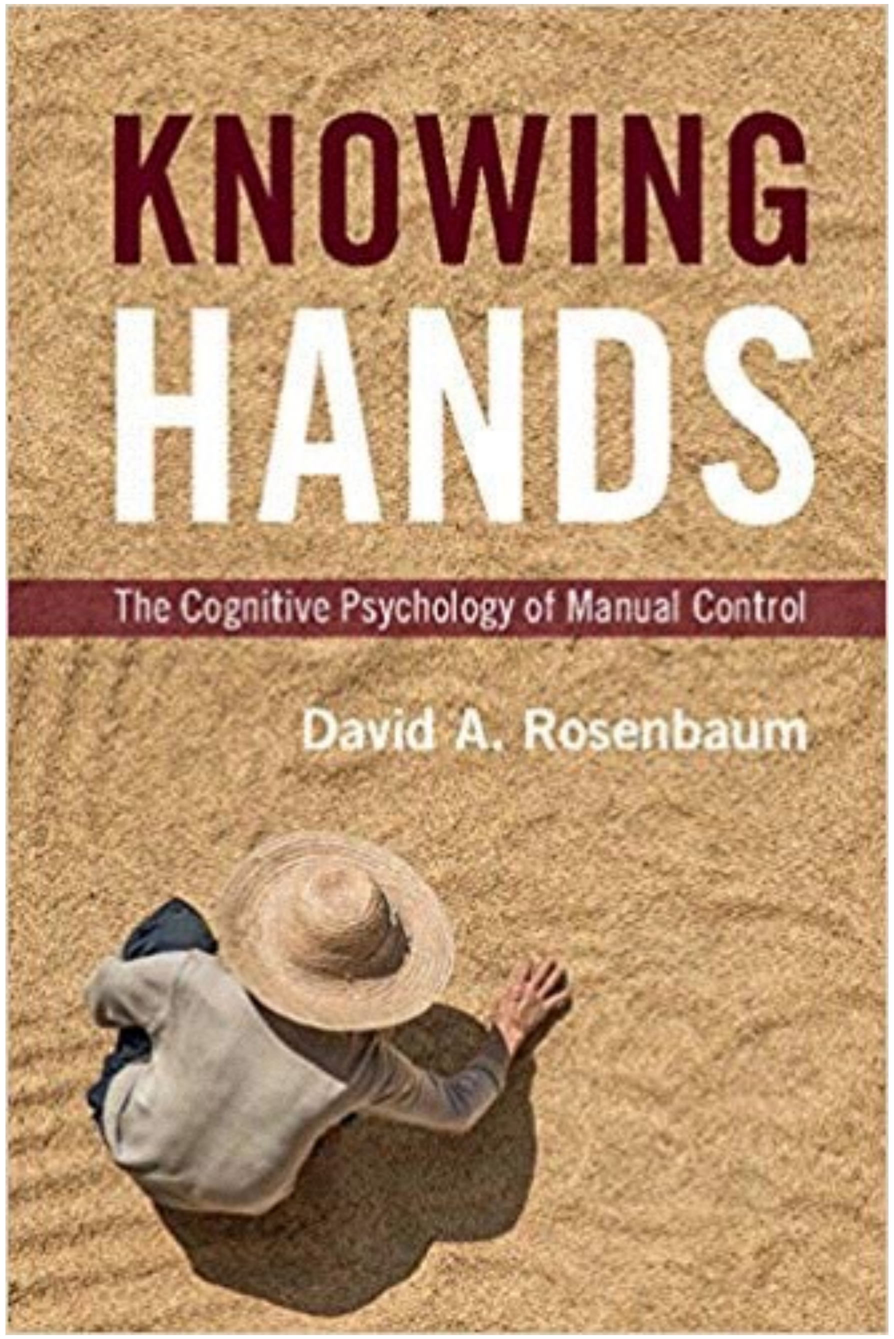
Fig. 14.1.

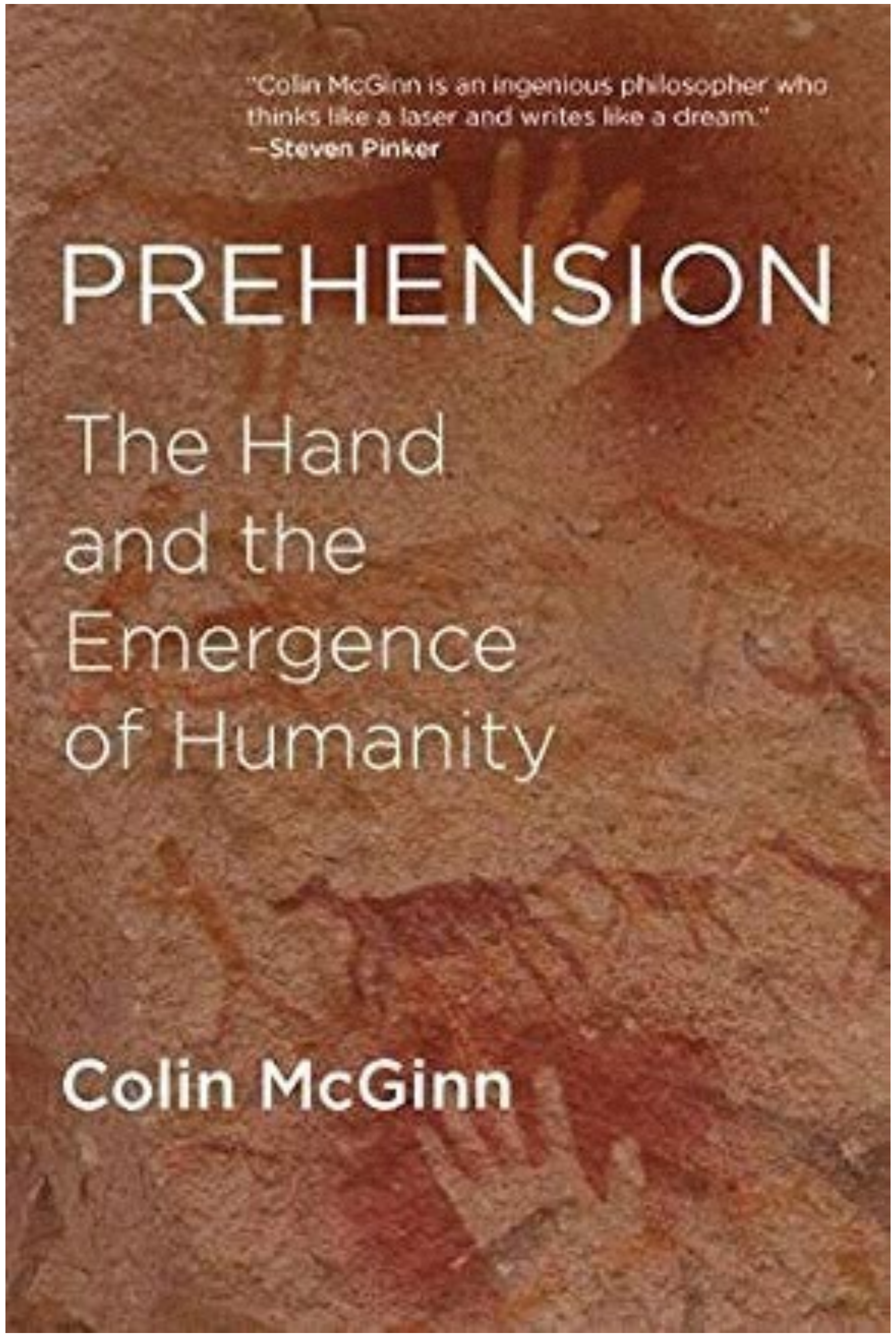
Le plaisir du fer forgé. La courbe ici est geste, rythme, mouvement. Elle laisse l'imagination libre d'un parcours lent ou vif, qui roule sur lui-même ou s'ouvre. Ses croisements permettent la fuite du regard et non pas, comme l'angle droit, le choc des lignes. Elle est prudence ou enthousiasme, rigueur et souplesse, elle est joie de l'action déployée en un ballet de lignes. Elle appelle ma caresse. Elle est plaisir de « palper par le regard ». Cette grille n'est pas obstacle, elle prend mon regard par la main, elle est invitation au geste gracieux de franchissement du seuil. Elle est promesse qu'une fois au-delà je ne serai pas enfermé mais délicatement séparé du dehors par sa barrière voluptueuse.

Previous research related to motormimetic cognition:

- *Sound-tracing*
- *Air instruments*
- *Free dance*
- Challenges of getting good data
- Challenges of analysis
- Challenges of knowing what we are looking for
- Focus now on *manual cognition*

Manual cognition:





Manual cognition:

- Our *hands* have a privileged role in human cognition
- Evolutionary basis for close links between perception, vocal apparatus, and manual skill development
- The classics of human gesture research, e.g. McNeill, Kendon, Goldin-Meadow, Kita, etc.
- Rosenbaum's ideas of *manual cognition* and *posture based theory* (PBT), in particular of *key-postures*, now applicable to sound-producing motion
- But first, some considerations of timescales:

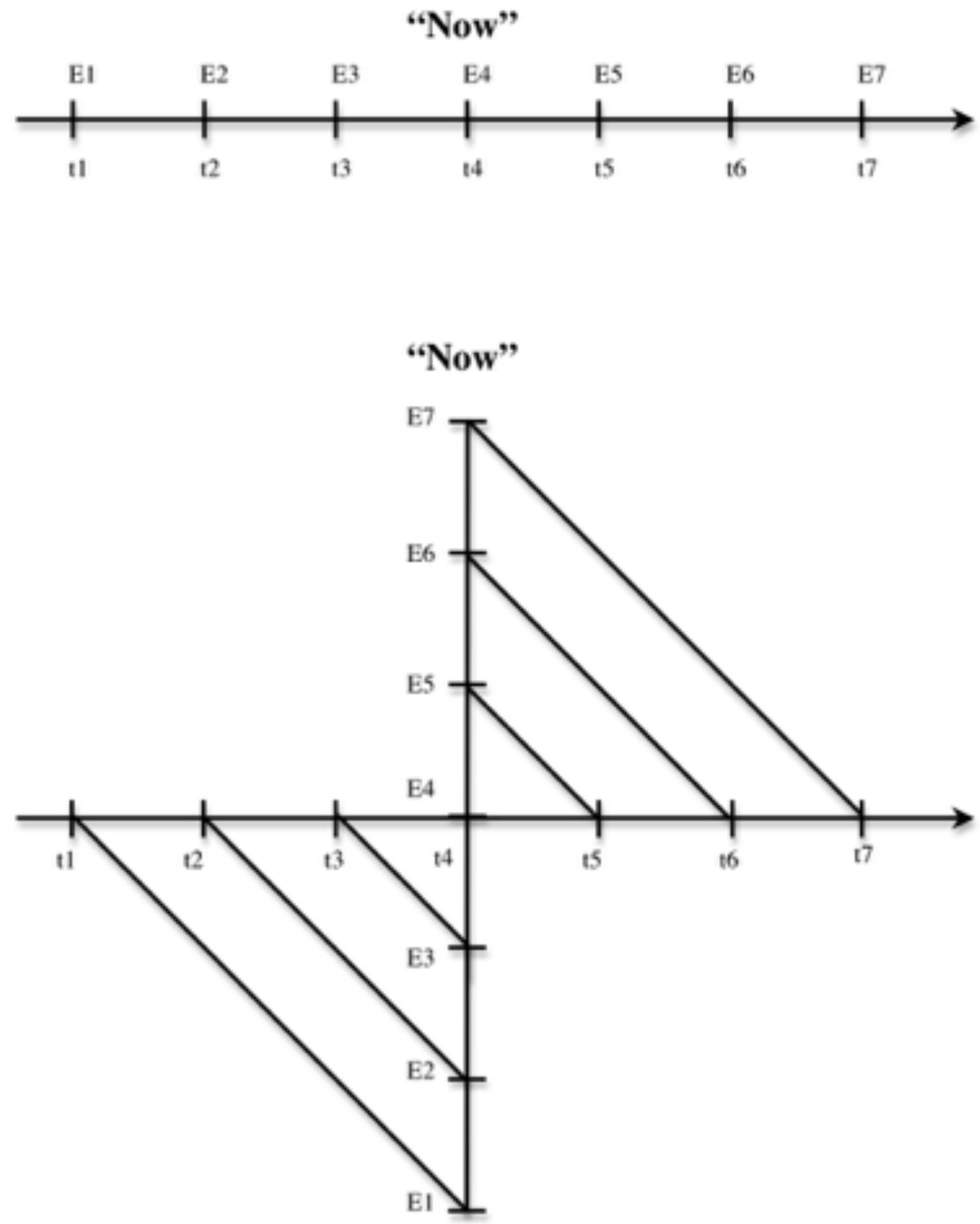
Timescales - a three-level scheme:

- *Sub-chunk level*: Continuous sound and motion below the chunk level of duration (i.e. below roughly 0.3 seconds)
- *Chunk level*: Holistically perceived fragments of sound and motion roughly in the 0.3 to 5 seconds range as with Pierre Schaeffer’s *sonic objects*, as in the following examples:
- *Supra-chunk level*: Concatenations of chunks into larger scale units, i.e. into sections, movements, and whole works

The chunk level timescale crucial because of anticipatory cognition as a quasi-stationary shape, to be activated by intermittent control and effort impulses (more on this later)

Timescales:

- More than 100 years of debate on continuity vs. discontinuity in perception and cognition from the time of Edmund Husserl, William Stern, and William James
- Husserl (1893): chunking by necessity, i.e. although sensations are unfolding sequentially (‘in time’), chunks also need to be perceived and conceived ‘instantaneously’ in ‘now-points’:



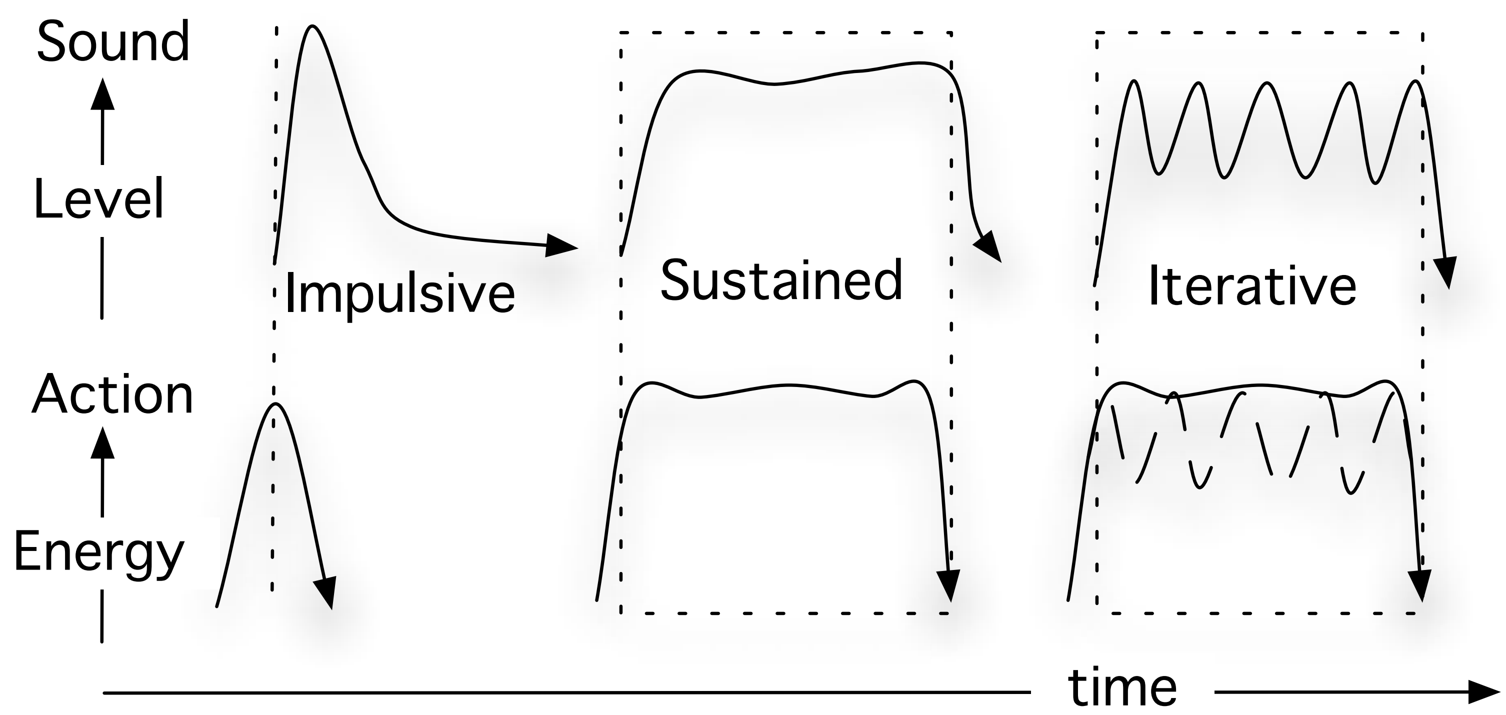
- The subjective experience of a *now-point* may encompass a segment of sequential unfolding, i.e. an entire chunk
- Now-points as combining the retrospective and prospective fits well with principles of *coarticulation in motor control*

Background for focus on sound-motion objects:

- Research on holistic perception of *auditory objects* (e.g. Griffiths and Warren 2004, Bizley and Cohen 2013)
- In performance: our own and others' research on sound-producing and sound-accompanying body motion as shapes (e.g. Godøy and Leman 2010)
- Research suggesting *quantal* elements in cognition (Godøy 2013) from Lashley to Klapp & Jagacinski and other gestalt-related projects, and also Grossberg's ART theory (2003)
- Recent research on *intermittent* motor control (e.g. Loram et al. 2011 and 2014) challenging notions of continuous control

Timescales of sound-motion objects:

- Considering some main categories of temporal unfolding a first stage in timescale analysis, cf. Schaffer's typology



from Godøy, Song, Nymoen, Haugen, and Jensenius (2016)

- These shapes are closely linked with various production constraints:

Typology of sonic objects by perceived motion

- Sound categories suggested by Pierre Schaeffer (1966), and that correspond to biomechanically distinct body motion categories:
- *Impulsive* = discontinuous effort
- *Sustained* = continuous effort
- *Iterative* = rapid series of impulses, i.e. continuous effort but bouncing back and forth such as in a drum roll (also note contextual smearing of resultant sound)
- *Phase-transitions* between categories based on duration and density of events

Some sub-chunk level morphological categories:

- *Grain* = Continuous movement across a rough surface, e.g. the 'brrrrrrr' of a double bass
- *Gait* (“Allure”) = Slower fluctuations in harmonic content, in pitch, in loudness, etc.
- Schaeffer also suggested these categories may apply across different timbres and instruments, e.g. a generic 'brrrrrr' grain from different sources

General point: Sound seems to be a good transducer of motion shape information, and motion shapes could be the basis for similarity differentiation of most perceived sonic features as in Schaeffer's theory:

	Qualification (2-3) / Evaluation (4-9) CRITERIA for musical perception	1	2	3	4	5	6	7	8	9
		TYPES typo-morphological summary	CLASSES musical morphology	GENRES musical characterology	SPECIES (site and width of the dimensions in the musical field) PITCH SITE OF TESSITURA	WIDTH OF VARIANCE	INTENSITY SITE OF WEIGHT	WIDTH OF RELIEF	DURATION variations of emergence IMPACT	MODULE
1	MASS	TONIC type N COMPLEX X VARIABLE Y ANY W,K,T	1. Pure sound 2. Tonic 3. Tonic group 4. Stiped 5. Nodal group 6. Node 7. Fringe	Characteristic TEXTURES of mass	7 octaves x 12 = 84 steps HARMONIC COLOUR REGISTERS extreme deep very deep deep medium deep normal medium high high very high extreme high [illegible]	HARMONIC INTERVAL COLOUR THICKNESS	WEIGHT OF HOMO-GENOUS MASS 1 ppp 2 pp 3 p 4 mf 5 f 6 ff 7 fff	PROFILE of the texture of a mass		(threshold of recognition for short sounds)
2	DYNAMICS	nil: homogenous H iterative Z weak weft N,X,T note shape N,X,N",X" impulsion N',X' cyclic Zk reiterated E accumulated A	Anamorphosis: SHOCKS RESONANCE Profiles: cresc. decresc. delta hollow biting Anamorphosis: flat	ATTACKS (dynamical timbre) 1. abrupt 2. steep 3. soft 4. flat pseudo attack biting 5. mild 6. pressed 7. nil			WEIGHT OF PRO-FILED MASS as function of its module 1 ppp 2 pp 3 p 4 mf 5 f 6 ff 7 fff	PROFILE MODULE weak medium strong	VARIATION OF PROFILE slow medium fast 1 2 3 4 5 6 7 8 9	SHORT SOUNDS MEASURED SOUNDS LONG SOUNDS
3	HAMONIC TIMBRE	either: GLOBAL TIMBRE or: secondary masses / timbre of the masses M1 tm1 M2 tm2 M3 tm3	(linked to the masses) NIL 1-7 TONIC 2 COMPLEX 6 CONTINUOUS 3-4 STRIPED 4-5	CHARACTER OF THE SOUNDING BODY hollow-filled round-sharp bright-dull etc.	COLOUR dark bright	WIDTH narrow wide 1 2 3 4	RICHNESS poor timbre rich timbre	density? volume? 1 2 3 4	variation: of width, of colour, of richness, from 1 to 9	(threshold of recognition for short sounds)
4	VARIATIONS MELODIC PROFILE	Unfolding / Profile / Anamorphosis Fluctation $\bar{N}$, $\bar{X}$ / N, X / N', X' Evolution $\bar{Y}$, T / Y, W / N', W' Modulation $\bar{G}$, P / G, M / G', K	(Only Y notes) podatus clivis toculus porrectus	character of profile: melodic pizz. trailing, etc.	or site of profile (see mass)	melodic variance weak medium strong	link of melodic profile with dynamic profile		slow medium fast 1 2 3 4 5 6 7 8 9	Partially or totally, se col. 3 start sustain decay
5	PROFILE OF MASS	Typological evolution Fluctation N /X or X/N Evolution Y/W or W/Y Modulation G/W or W/G	(Only thickness) dilatated delta slimming hollowing	characteristic evolution in mass in harmonic timbre	consequences for the tessitura or the colour (mass and harmonic timbre)	melodic variance weak medium strong	link of mass profile with dynamic profile		slow medium fast 1 2 3 4 5 6 7 8 9	Partially or totally, se col. 3 start sustain decay
6	SUSTAIN GRAIN	Pure or mixed by resonance scrubbing iteration	Trembling / Seething / Limpid rough / dull / smooth large / clear / fine	harmonic compact-harmonic compact compact-discontinuous discontinuous discontinuous-harmonic	GRAIN SEEN AS MASS OR TIMBRE colour of grain	thickness of grain	Relative weight GRAIN-MASS LINKED	Dynamic texture of grain weak medium strong	variation of grain width/speed from 1 to 9	tight adjusted loose 1 2 3 4 5 6 7 8 9
7	GAIT	Pure or mixed mechanical living natural	order / fluctuation / disorder 1 2 3 4 5 6 7 8 9	regular cyclic vibrato progressive irregular steep fall damped incident		variance of pitch of the gait weak medium strong	Relative weight allure/dynamic	Dynamic relief of gait weak medium strong	variation of gait width/speed from 1 to 9	tight adjusted loose 1 2 3 4 5 6 7 8 9

Holistic perception and conception of chunks:

- Enigma of how the sequential can be instantaneous
- Possible answer for sound: echoic memory
- Possible answer for movement: also a kind of short-term memory
- Various evidence for *anticipation* in motor control from Lashley to Rosenbaum (see Rosenbaum et al. 2007 for a lucid overview)
- Evidence for motion hierarchies and goal-directed motor control (Grafton and Hamilton 2007)
- An example of the challenges:

Criteria for motion boundaries:

- Problem: we are never still!
- Thresholding, i.e. relative stillness
- Also need to look at acceleration and further derivatives such as jerk
- Distinguish between periodicity detection (by repeats) and stop-start boundaries
- Probably multiple cues at work in perception of chunks
- Given these facts, substantial challenges in making machines/software detect humanly meaningful motion boundaries
- Hogan and Sternad (2007):

Discrete movements:

- "In order for two movements to be distinct, there must be a gap between them, an interval of no movement. That is, a discrete movement has an unambiguously identifiable start and stop; *discrete* movements are bounded by *distinct* postures."
- Posture: "the terms “stop”, “pause” and “pose” are all synonymous with “posture” which we define as the absence of movement."
- Thus: "*Preliminary definition* A fixed posture occupies a non-zero duration in which no movement occurs."
- But a purely signal-driven, bottom-up approach may not be so easy to implement….

Main issues of music-related motor control:

- It seems we need to understand more of motor control
- Motor control = "…the systematic regulation of movement in organisms that possess a nervous system. Motor control includes movement functions which can be attributed to reflex, and to volition. Motor control as a field of study is primarily a sub-discipline of psychology or neurology." - Wikipedia
- Music-related motor control in *sound-producing body motion* (performance) and in *sound-accompanying body motion* (dance, walking, gesticulating)
- Motor control in music places strong demands on timing and precision in relation to sound
- Some useful introductory texts:

Some useful introductory texts

- Rosenbaum, D. (2009). *Human Motor Control* (Second Edition). Burlington, MA.: Academic Press. Also available for download: https://www.sciencedirect.com/science/book/9780123742261

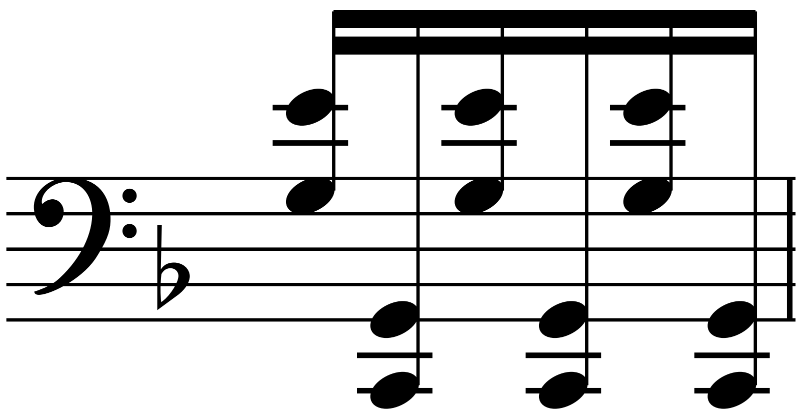
- Gollhofer, A., and Taube, W. (2015). *Routledge Handbook of Motor Control and Motor Learning*. New York: Routledge

- Godøy, R. I. (2014). Understanding Coarticulation in Musical Experience. In M. Aramaki, M. Derrien, R. Kronland-Martinet & S. Ystad (Eds.): *Lecture Notes in Computer Science 8905*. Berlin: Springer, 535-547, and references listed there

- Various *constraints* could give us some clues about chunk-formation in music

Sound-production constraints:

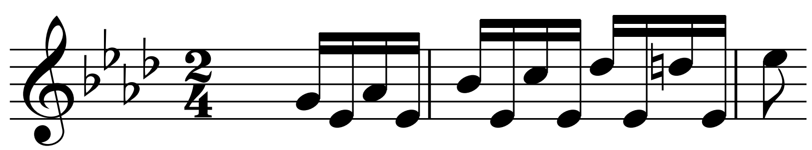
- *Instruments*: acoustics, ergonomics, expression
- *Biomechanics*: avoid fatigue, minimise energy cost
- *Motor control*: accuracy and high speed motion necessitating hierarchical planning
- *Idioms* of instruments/voice: easy motion tasks resulting in well-sounding fragments



Sound-production constraints:

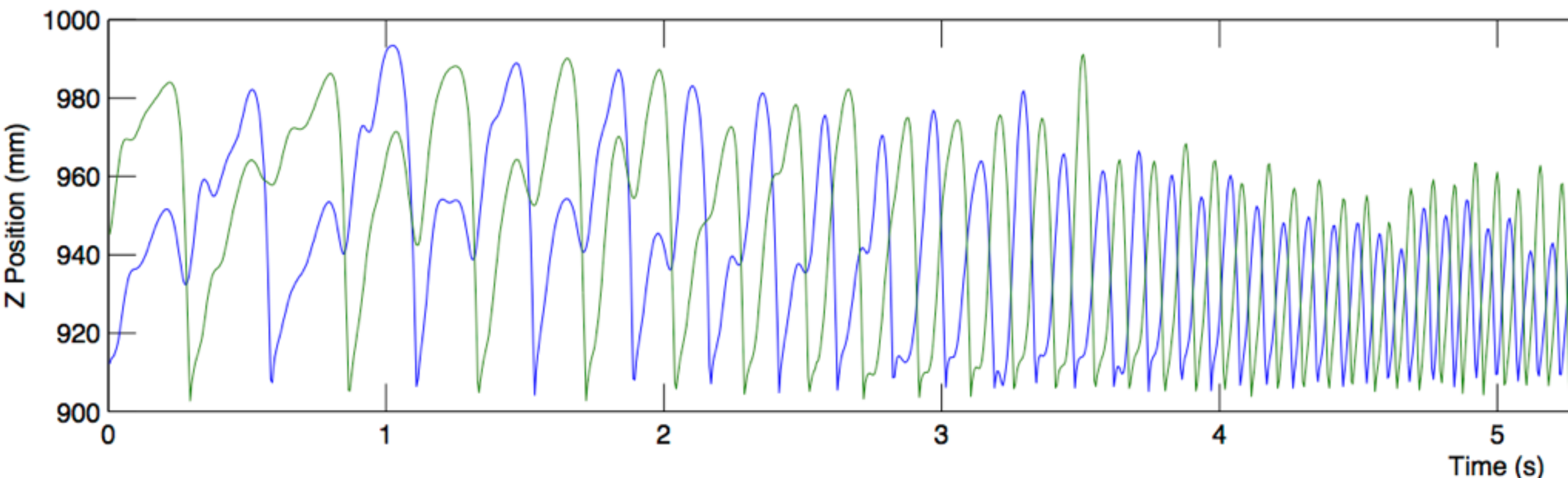
- Vocal example: *ti-ku-ti-ku* vs. *ti-ti-ti-ti* where one is easier than the other

- Constraints in musical translations:

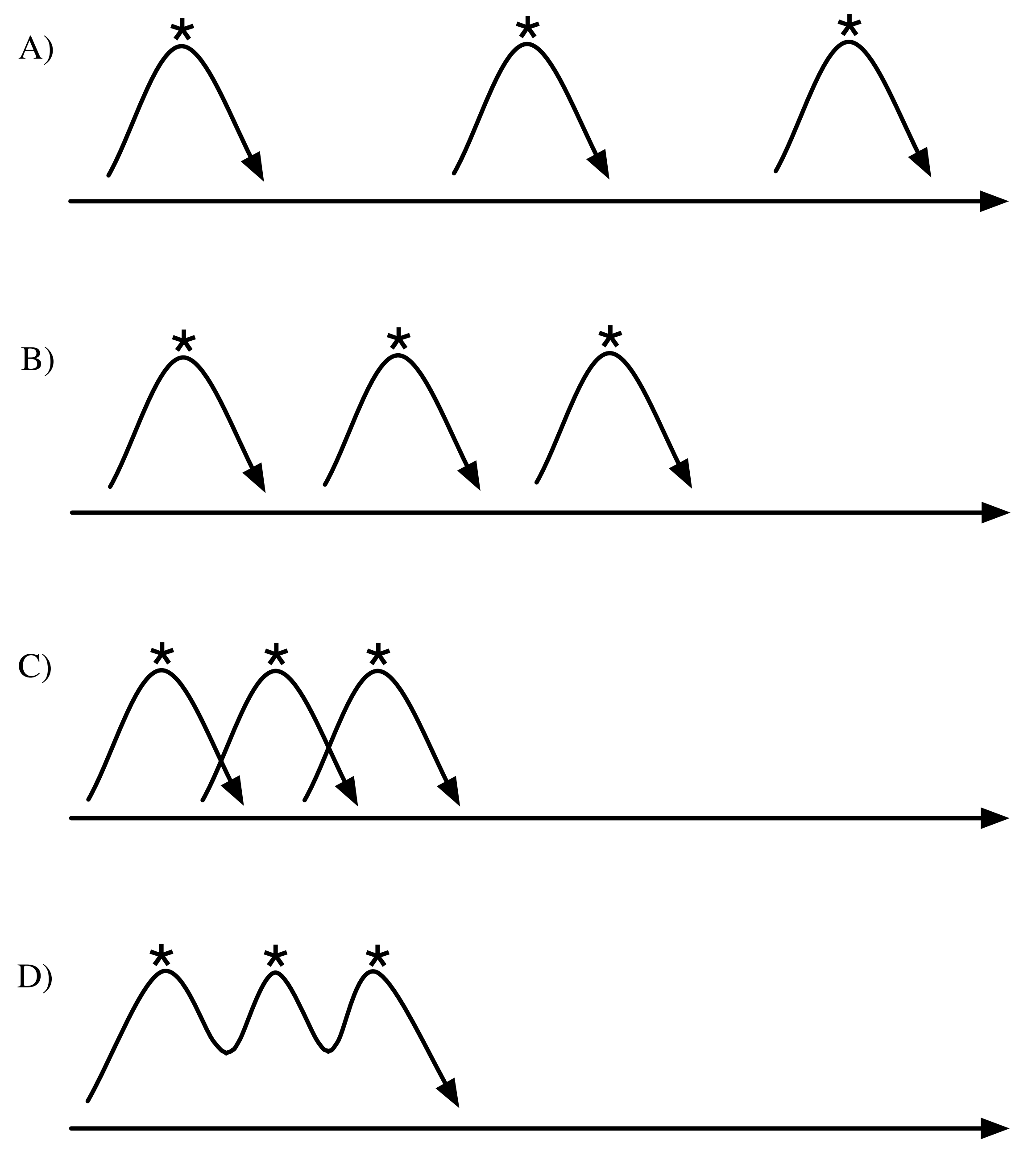


Timescales constraints in sound-production:

- Although large span between longest and shortest durations of sound producing motion, limits in either direction
- Various *biomechanical constraints* (maximum speed, need for rests, posture changes, etc.), *attention constraints* (with a need to make motion automatic), and *coarticulation* (more on this later), at different timescales in sound-production
- And: so-called *phase transition* thresholds in motion (Haken, Kelso, and Bunz 1985), e.g. between singular strokes and tremolo:

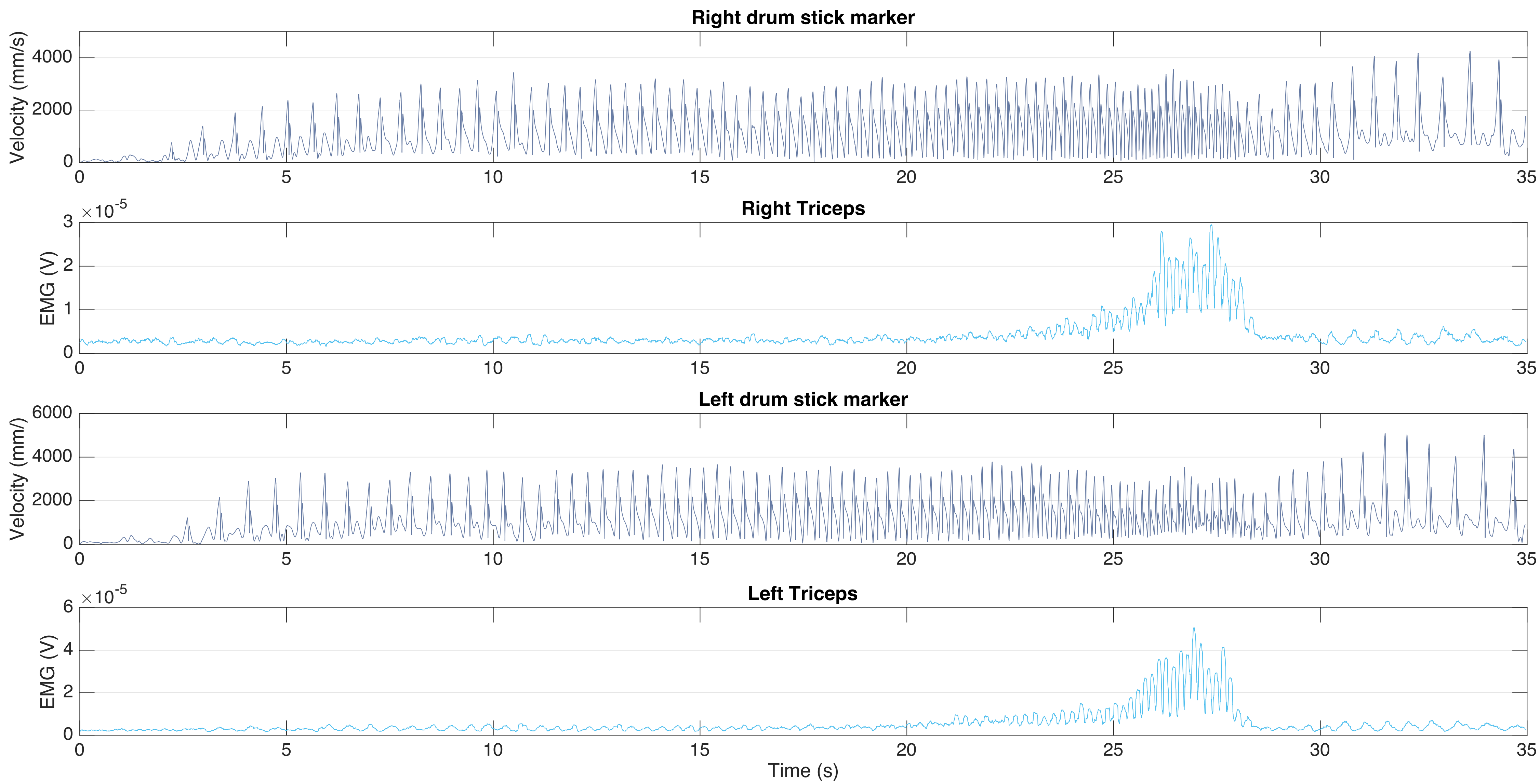


Phase-transition, from individual to iterative sounds:



Phase-transition also involves change of effector muscle use:

EMG of accelerando and ritardando in drumming



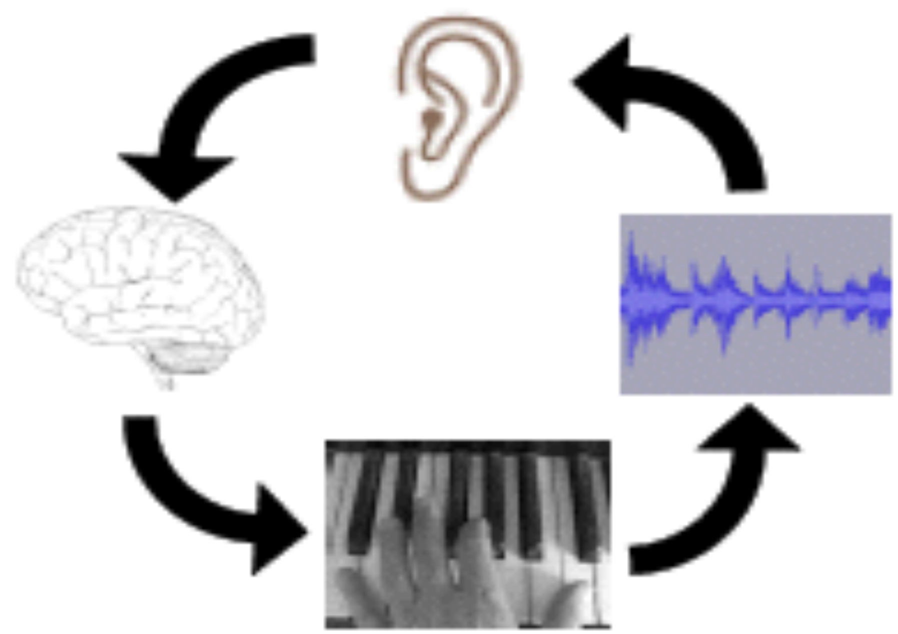
See Gonzalez Sanchez, Dahl, Hatfield, and Godøy (2019) for details on EMG, mocap, and fluency in performance

Constraints:

- Combined *biomechanical* and *attention constraints*, e.g. the so-called *psychological refractory period* (PRP) (Klapp & Jagacinski 2011), necessitates *anticipation*, and hence also *intermittency in motor control*
- The psychological refractory period threshold is around 0.5 seconds, and seems also to be the source of so-called *fakes* in sports:

Timescales constraints in sound-production:

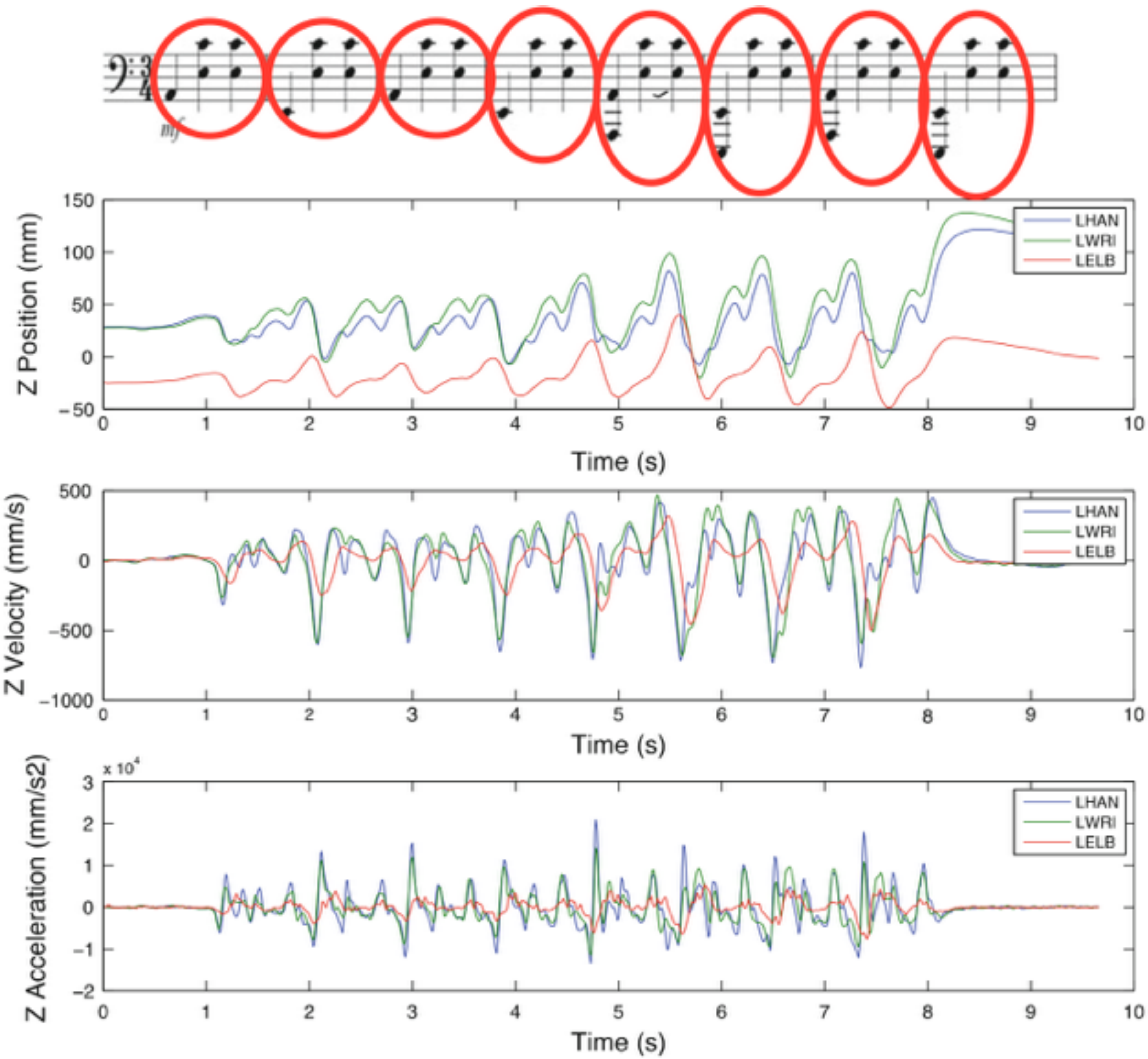
- Feedback-based control is probably intermittent, because everything takes time
- Long-lasting discussion of so-called *open loop* vs. *closed loop* in human motor control



- Tentative conclusion: *several constraints converge in making musical performance proceed by a series of impulses, each impulse engendering one chunk of sound-motion*

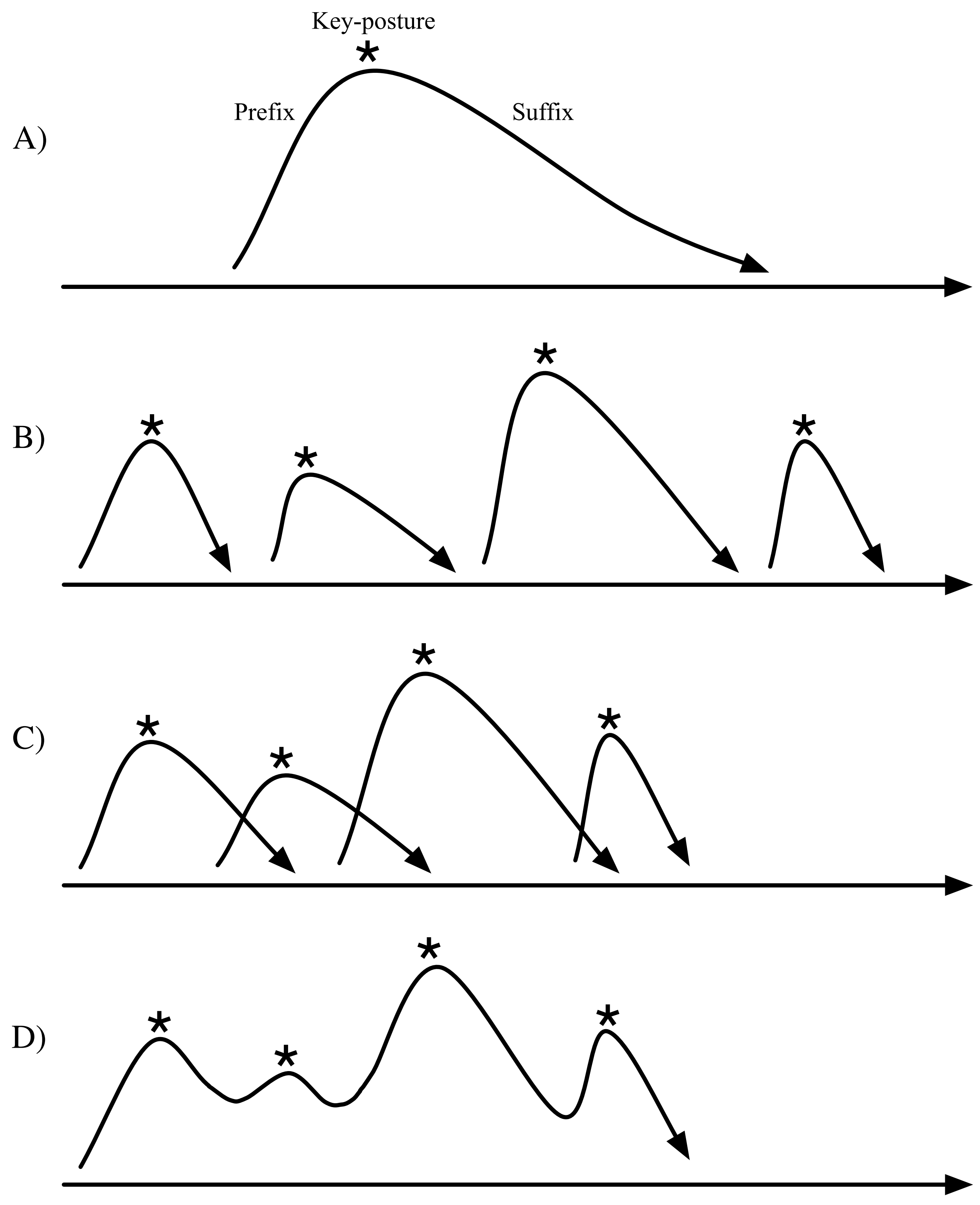
Sources of sound-motion chunking:

- Necessary pre-programming of chunk-level body motion
- We can understand body motion as *hierarchical* and *goal-directed* (e.g. Grafton and Hamilton 2007) and as centred on what we call *key-postures* at salient moments in time, inspired by (Rosenbaum et al. 2007)
- We have continuous trajectories between key-postures
- All motion and sound events within such trajectories are fused into coherent chunks by *coarticulation*, i.e. the fusion of sub-chunk level body motion and sounds into holistically perceived chunks of motion and sounds



mf
Z Position (mm)
Time (s)
LHAN
LWRI
LELB
Z Velocity (mm/s)
Time (s)
Z Acceleration (mm/s2)
x 10^4
Time (s)

Coarticulation, from individual to fused motion and sounds:



Principles of coarticulation:

- *Temporal coarticulation*: otherwise singular events embedded in a context
- Past events influence present events, i.e. position and shape of effectors are determined by recent motion, by *spillover* effects
- Future events influence present events, i.e. position and shape of effectors are determined by preparation for future motion, *anticipatory* effects
- *Spatial coarticulation*: motion in one effector (e.g. hand) recruits motion in other effectors (e.g. arm, shoulder, torso)
- Seems to be a biomechanical necessity
- Seems to be a motor control necessity, i.e. anticipation in motor control

Principles of coarticulation:

Coarticulation can be seen 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." (Rosenbaum 1991, 15)

Coarticulation in various domains:

- Everyday tasks, e.g. reaching and lifting
- Animation
- Facial movements
- Fingerspelling
- Handwriting
- Music, but not well studied here
- Much studied in speech (see Hardcastle and Hewlett 1999 for an overview)

Coarticulation in speech:

'Look into a mirror and say (rather deliberately) the word tulip. If you look closely, you will notice that your lips round before you say "t", Speech scientists call this phenomenon anticipatory lip rounding.'...'anticipatory lip rounding suggests that a plan for the entire word is available before the word is produced. If "tulip" were produced in a piece-meal fashion, with each sound planned only after the preceding sound was produced, the rounding of the lips required of "u" would only occur after "t" was uttered.' (Rosenbaum 1991: 14) And: 'Anticipatory lip rounding illustrates a general tendency that any theory of serial ordering must account for–the tendency of effectors to coarticulate.' (ibid: 15)

Some studies of coarticulation in sound production:

- In piano playing: fingers move to optimal position before hitting key (Engel, Flanders, and Soechting 1997) and contextual muscle activations (Wings et al. 2013)
- In string playing: left hand fingers in place in position well before playing of tones (Wiesendanger, Baader and Kazennikov 2006) and contextual smearing of bowing movements (Rasamimanana and Bevilacqua 2008)
- In drumming: In some cases, a drummer may start to prepare an accented stoke several strokes in advance (Dahl 2004)
- For some examples of our own work with infrared motion capture data of piano and marimba performance (see Godøy, Jensenius, and Nymoen 2010; Godøy 2014)

Intermittent key-postures in coarticulation:

- So far: We believe there are indications of coarticulation in sound-motion chunks, both in position and velocity data
- And: We believe that coarticulation concerns both the sound and the sound-producing motion, hence both perception and production
- But we also believe these sound-motion chunks are centred on key-postures at salient points in the music such as downbeats, other accents, and melodic peaks, surrounded by *prefixes* and *suffixes*
- Key-postures well known from animation as salient instants in the motion:


Pøh! Etter lyspæren å dømme var det helt tilbake i Klondike-tiden.
Klage! Klage! **Alltid** klage!
Ja, hvordan kan jeg... **opps!**
KNEKK!
KRASJ!
Frøken Vable gikk forresten ut et øyeblikk. Kan du overta plassen hennes mens du likevel slapper av?
J-ja, selvfølgelig...

Intermittent key-postures in coarticulation:

- Actually, a similar idea of coarticulation centred around key-postures has been presented in linguistics:

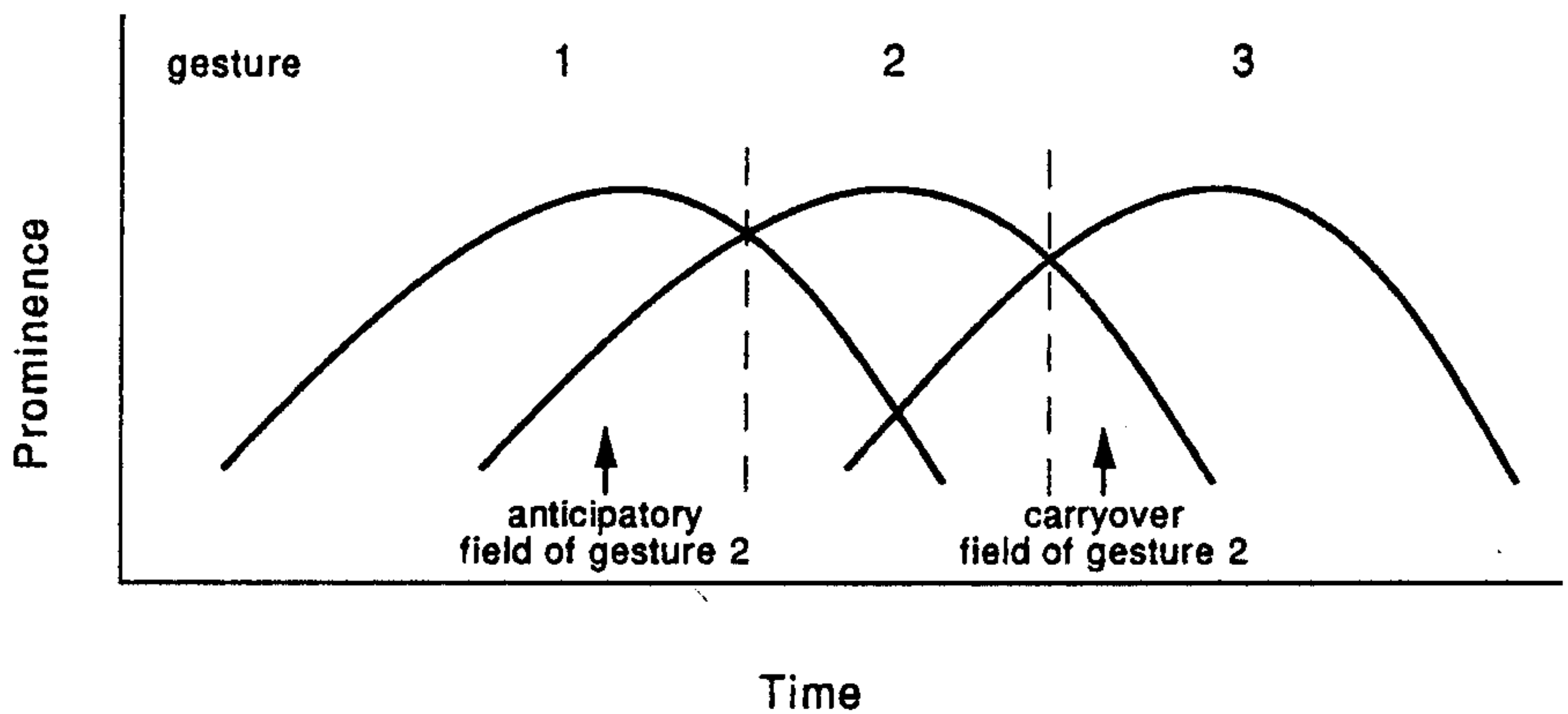
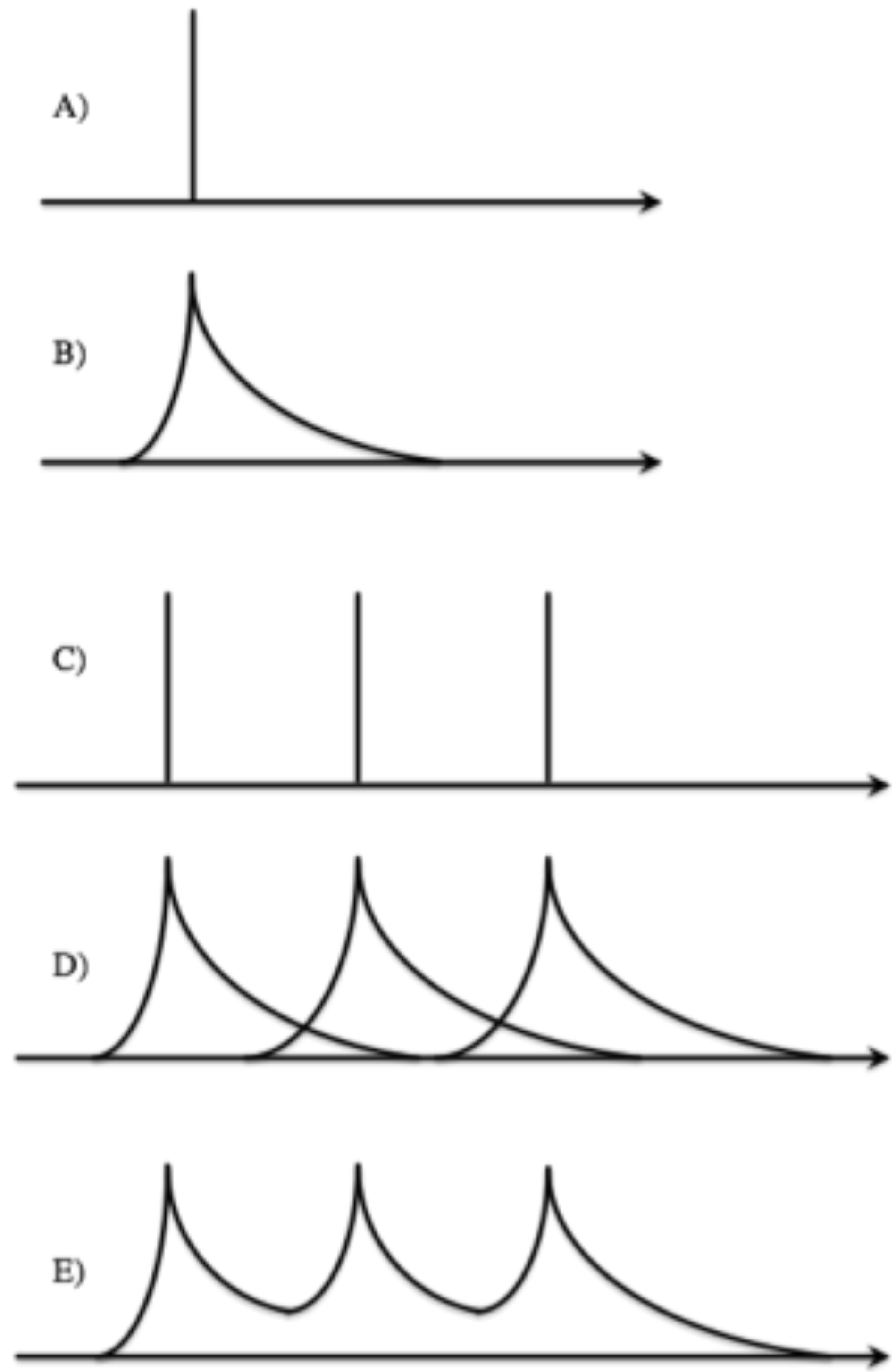


Figure 2.5 Representation of three overlapping phonetic gestures (from Fowler and Saltzman 1993). See text for details.

Intermittent key-postures in coarticulation:

- One advantage of this model is that it can accommodate continuous, supra-chunk level sound-motion, since suffixes of past key-postures may overlap with prefixes of new key-postures, resulting in sensations of continuity
- This may also address the problem of chunking that perceivers experience but are hard to pinpoint in motion data
- Thus: a novel understanding of chunking where intermittent key-postures at salient moments in time are primordial and boundaries between chunks are secondary or may be more fluid, i.e. suffixes and prefixes may overlap


A)
B)
C)
D)
E)

Elements converging in *musical instants*:

- Constraints of our organism suggest intermittent intermittent, point-by-point, motor control
- In particular, the PRP (the psychological refractory period) is seen as resulting in intermittent motor control
- Notably so, this claim is here limited to the PRP timescale, i.e. the very approximate 0.3 to 2.0 seconds duration
- Hence, a combination of pre-programmed motion shape at this timescale and an impulse
- Similarity with impulse-response phenomena (a Dirac impulse convolved with a system) as a general model:

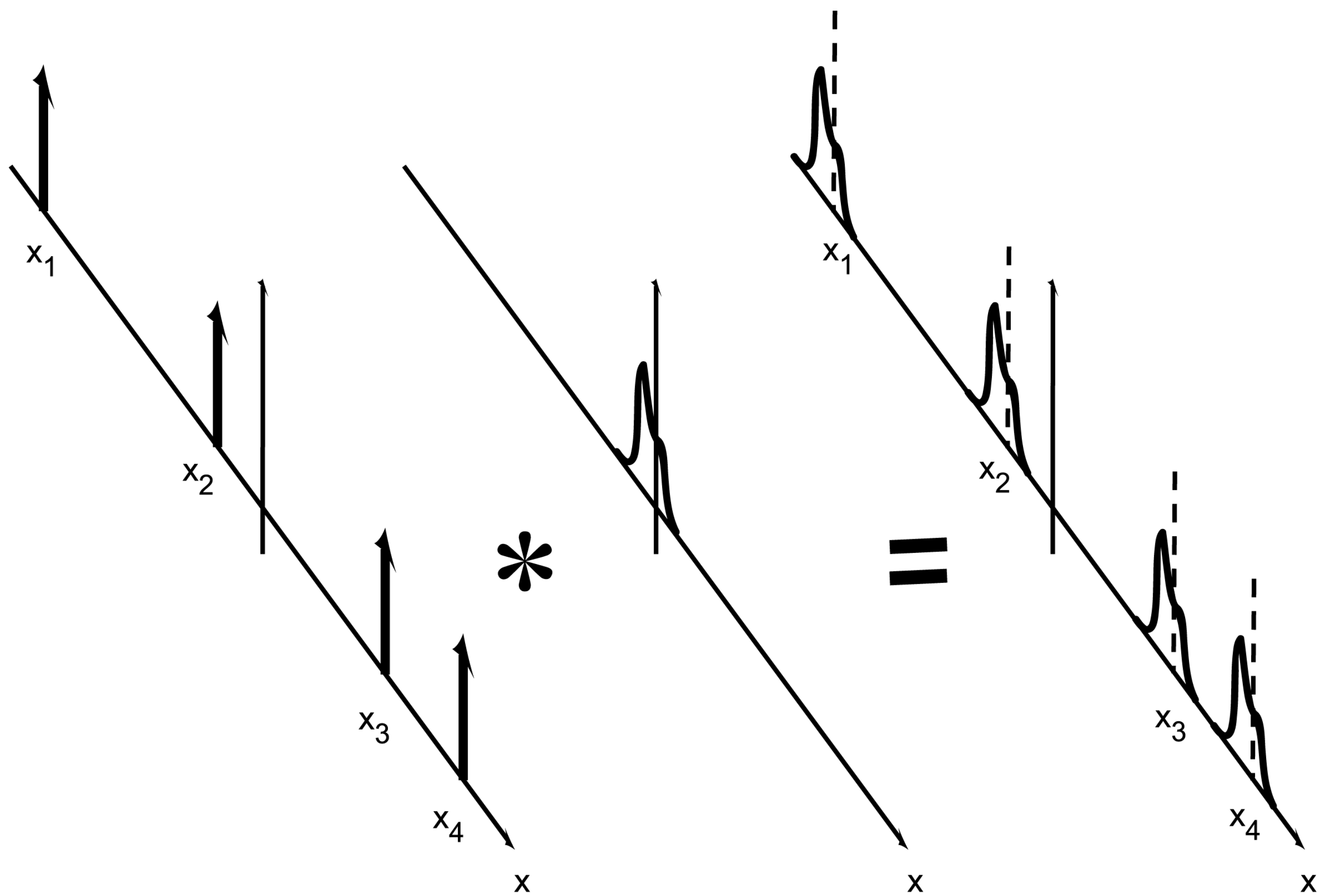


Figure 2.8: The convolution of a series of displaced delta functions centred at x_1, x_2, x_3 and x_4 with a continuous function. The convolution can be viewed as a smearing of the sharp delta functions or a quadruplication and displacement of the continuous function.

from Paul Curmi, Advanced Optics, Unit 2: Fourier Transforms and the Convolution Theorem

Consequences for sound-motion analysis:

- Onsets of sound result from body motion, hence, need to *study goal-points of sound-producing body motion*!
- Understand *thresholds for sound output* on instruments and voice, i.e. the *all-or-nothing* nature of output
- Look for *ballistic contraction* in the EMG data
- Look for *discontinuities* (velocity reversal, jerk) in the motion trajectory data
- Look for *key-postures*
- Look for sound-motion objects at the *PRP timescale*
- Understand the relationship between *discontinuity in motion generation* and *apparent continuity in output*

Relevant research:

- Publications on intermittent control, e.g. Karniel 2013, Loram et al. 2014, Sakaguchi et al. 2015
- Action gestalts as solution to the psychological refractory period (Klapp and Jagacinski 2011)
- Impulse-response implemented in handwriting motion (Plamondon et al. 2013) and in graffiti motion (Berio et al. 2017), as summarised here:

"In our work we rely on a family of models known as the *Kinematic Theory of Rapid Human Movements*, mainly developed by R. Plamondon et al. in an extensive body of work since the 90's"… "They show that if we consider that a movement is the result of the parallel and hierarchical interaction of a large number of coupled linear systems, the impulse response of such a system to a centrally generated command asymptotically converges to a lognormal function. This assumption is attractive from a modelling perspective because it abstracts the high complexity of the neuromuscular system in charge of generating movements with a relatively simple mathematical model, which further provides state of the art reconstruction of human velocity data."

Intermittent key-postures in coarticulation:

- Challenge: what are salient points in time?
- Downbeats and other accents, yes, but what are downbeats?
- *Downbeat*, a strangely under-researched concept....
- One hypothesis: downbeat = the point of velocity reversal, usually preceded by high acceleration, or for convenience, *the moment of impulse*, hence the idea of *impulse-centred chunking*
- Typical of so-called *ballistic* motion (hitting, kicking), but arguably also valid for the initial phases of sustained and iterative motion
- Biomechanical need for exploiting rebound energy (the bounce) and need for rests, e.g. the so-called *pre-motion silent period* in ballistic motion EMG signals:

Pre-motion silent period:

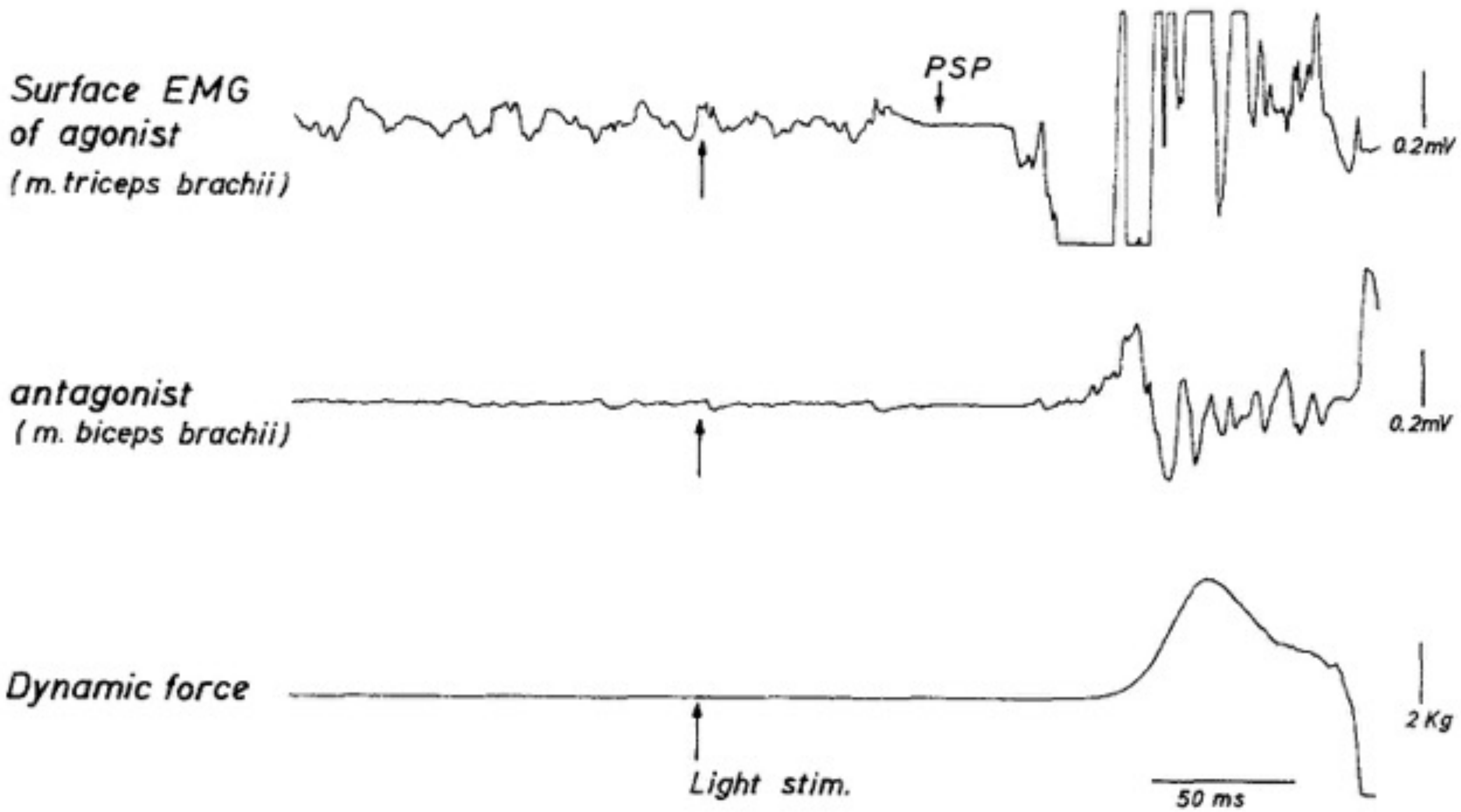


Fig. 1. A typical record of surface electromyogram (EMG) and dynamic force curve during a rapid elbow extension. *Top:* Surface EMG recorded from elbow-extensor muscles (m. triceps brachii). *Middle:* Surface EMG of antagonistic muscles (m. biceps brachii). *Bottom:* Dynamic force curve recorded simultaneously. *Arrows* show time of light stimulus. To illustrate the pre-motion silent period (PSP) clearly, the *top trace* of EMG is plotted with high vertical gain so that the EMG burst is saturated. PSP is observed prior to the EMG burst of the extensor muscles *(top trace)*

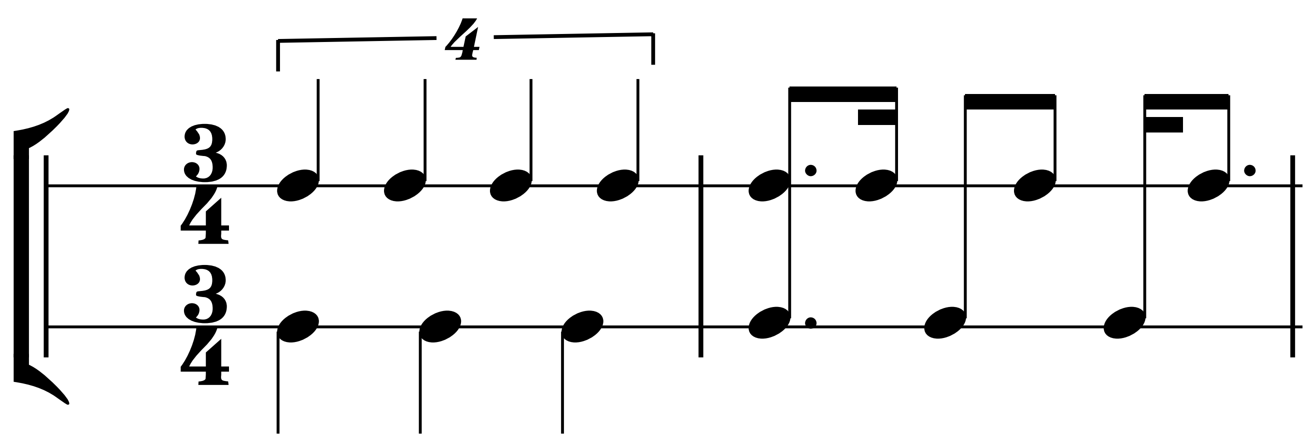
from Aoki, Tsukahara, and Yabe (1989)

Entire chunk as a singular impulse-driven sound-motion object:

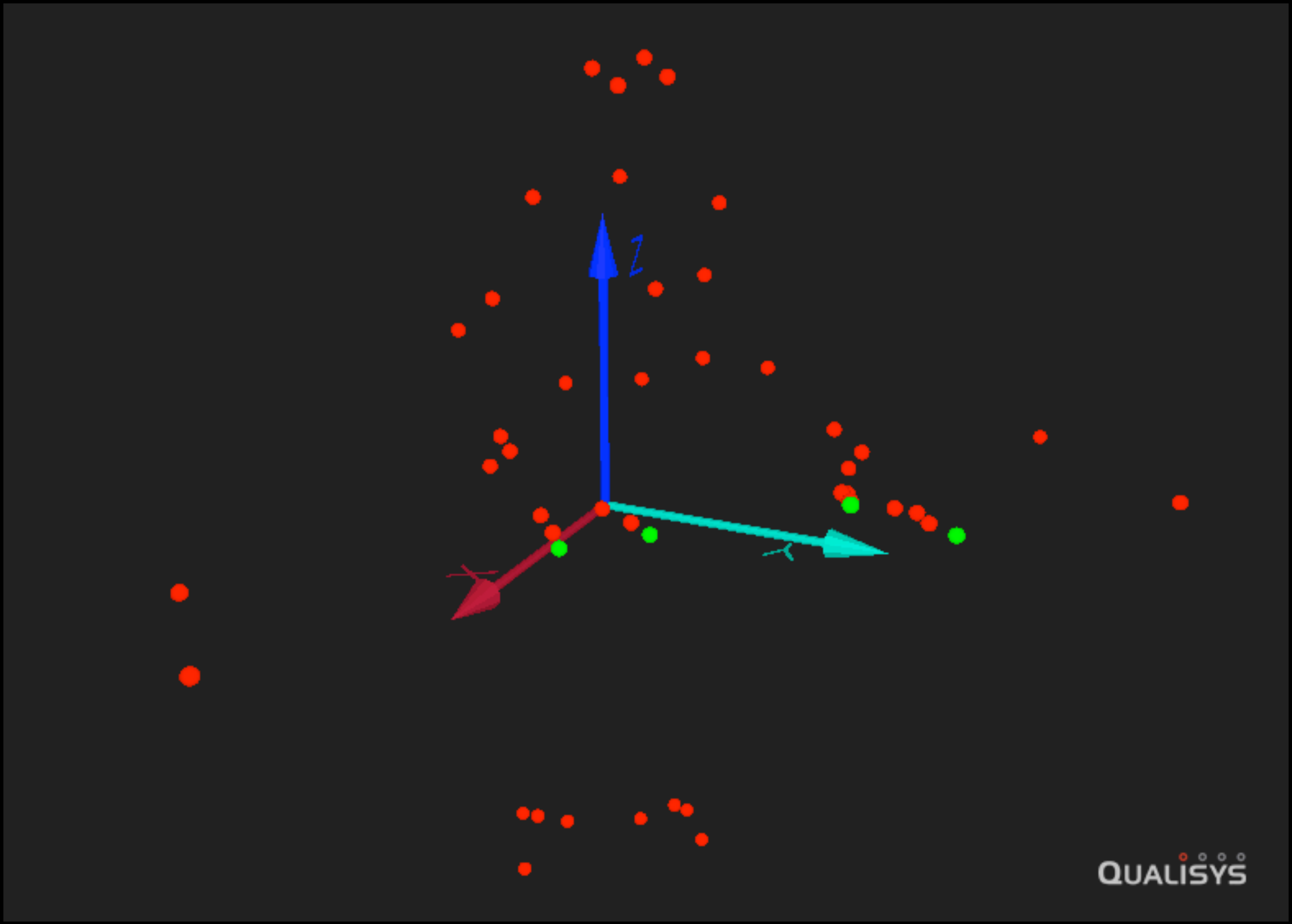
- The case of polyrhythm: "The limitation to only one motor Gestalt may be analogous to limits that arise with visual patterns such as the Necker cube. That figure can be perceived in only one of its configurations at any given instant. In either configuration, however, all of the lines of the cube are perceived simultaneously as one pattern. Thus, the Gestalt is not restricted in terms of the number of lines that can be perceived. Instead, the limit is that only one organization can be activated. Similarly, the limit in concurrent motor actions is assumed not to lie in the number of muscles that can be controlled, but, instead, the limit is that only one action pattern can be active." (Klapp, Nelson, and Jagacinski 1998, 318) - Suggestion: *even rather complex patterns of motion may be conceived and perceived as a single chunk in motor control*.

Sound-motion objects, divergent or coherent?

- *Egocentric* agency perspective on sound-producing motion
- Complex and *multi-effector* motion (e.g. bimanual and bipedal in drum set performance) conceived as unitary ('monophonic') objects (see e.g. Klapp et al. 1998):



- Hence: the holistic perception of (sometimes also quite complex) sound-motion texture objects, such as in the two following examples:



Z
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X
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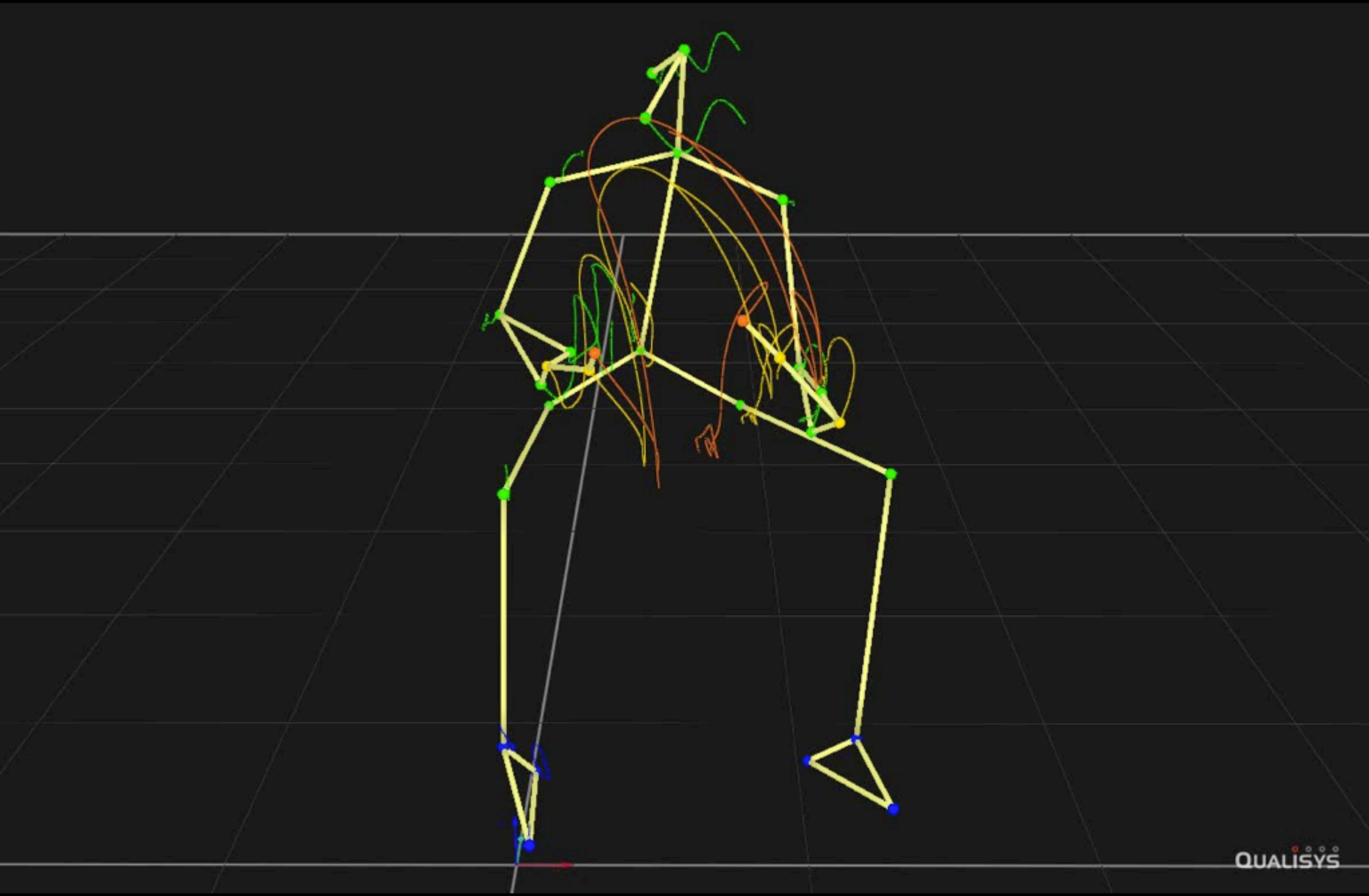


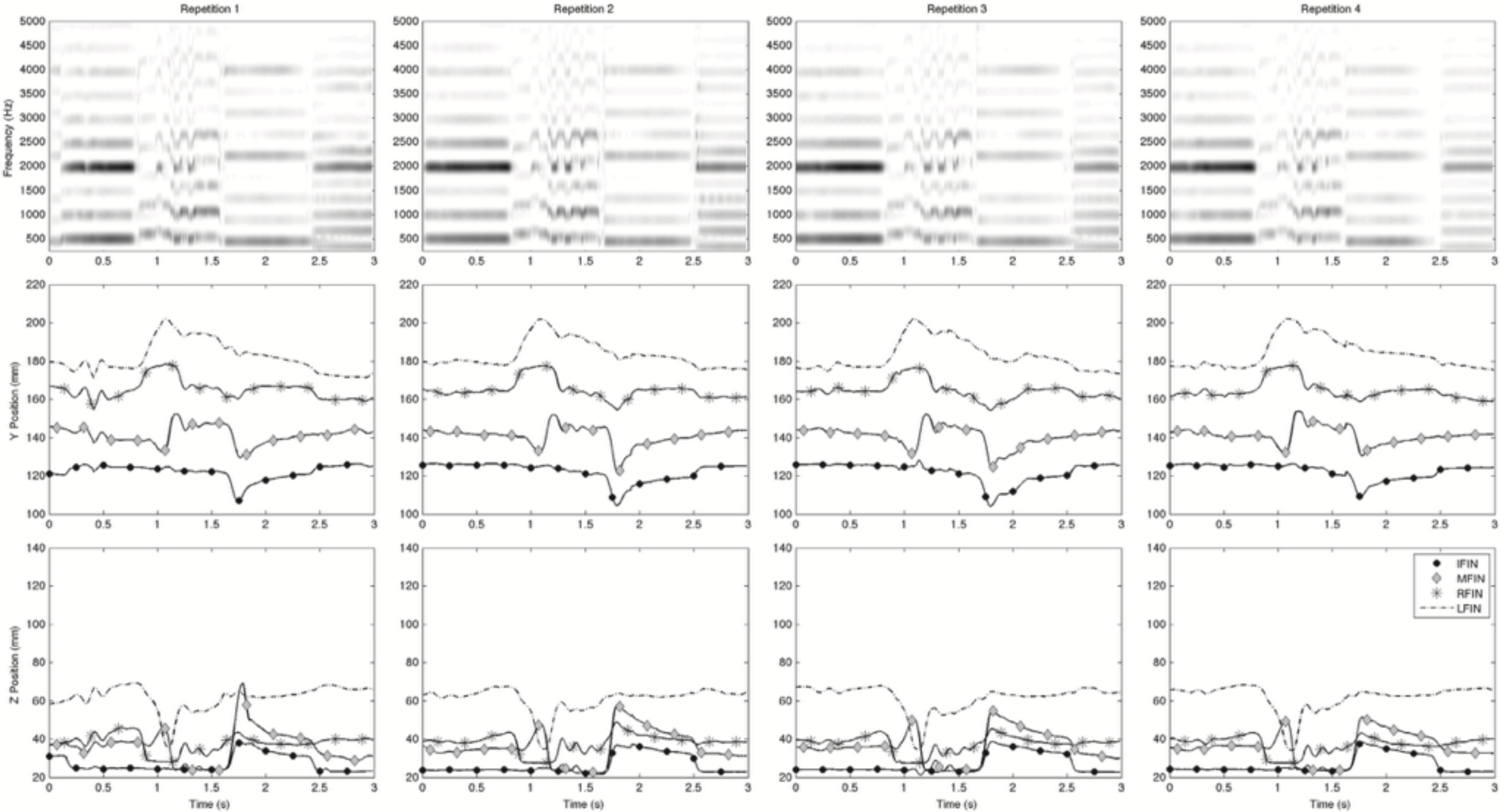
Drumset fills:

- Typically fast motion in fills
- Requires high degree of pre-programming
- Requires much anticipatory motion and hence coarticulation
- Requires also whole body activation, i.e. torso rotation in order to reach the different instruments

Ornaments:

- Typically very fast motion
- Requires high degree of pre-programming
- Seems to be quite consistent with repeats

Violin ornaments:



Motion consistency between repeated ornaments by a single fiddler. An optical motion-capture system tracked the trajectories of four markers (IFIN, MFIN, RFIN, LFIN). The first row shows spectrograms of four repetitions, each lasting three seconds. The second row shows finger movements along the fingerboard, and the last row shows the vertical movements of the fingers.

In summary

- *Intermittent motor control* based on constraints of our motor control system: relatively slow, hence, needs pre-programming
- *Open loop*, *feed forward* control
- *Serial ballistic control* = point-by-point control impulses, and no control inputs between these points
- Hence, intermittent control impulses resulting in *piecewise (within-chunk) continuous motion*
- Intermittency may thus (paradoxically so) foster continuity
- A reconciliation of discontinuity and continuity

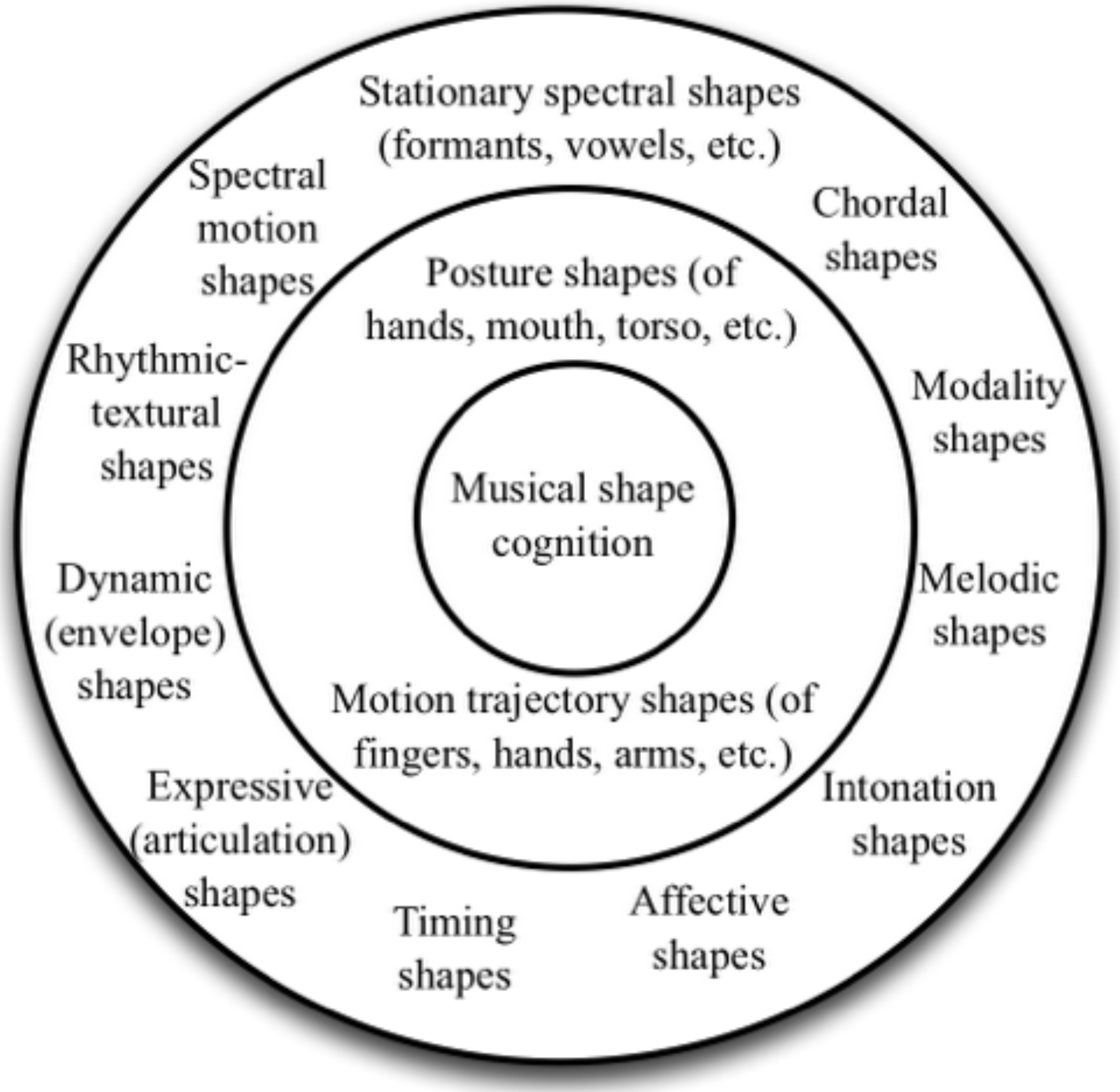
Testable hypotheses concerning impulse-driven sound-motion objects:

- Coarticulation in sound-producing body motion, i.e. within-chunk fusion of motion
- Coarticulation in resultant musical sound, i.e. within-chunk fusion of sound
- Intermittent effort
- Intermittent control
- Velocity peaks and impacts at key-postures
- Model in view of similarity with impulse-response phenomena (the Dirac impulse convolved with a system, i.e. a piecewise stationary shape) as a general model

Some major challenges here:

- Get good EMG data on effort distribution
- More precise motion capture data
- Signal processing that better capture intermittency in sound-producing motion
- Contributions from other cognitive sciences on intermittency
- Demonstrate practical applications of impulse-driven sound-motion objects in composition, improvisation, and performance
- Substantiate links between intermittency and shape cognition:

Musical shape cognition = thinking chunks of fused sound and body motion and their salient features at different timescales as *shapes*:



The basis for musical shape cognition = a *motor theory perspective on music*, recognising body motion sensations as manifest in parallel with sound sensations in musical experience.

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