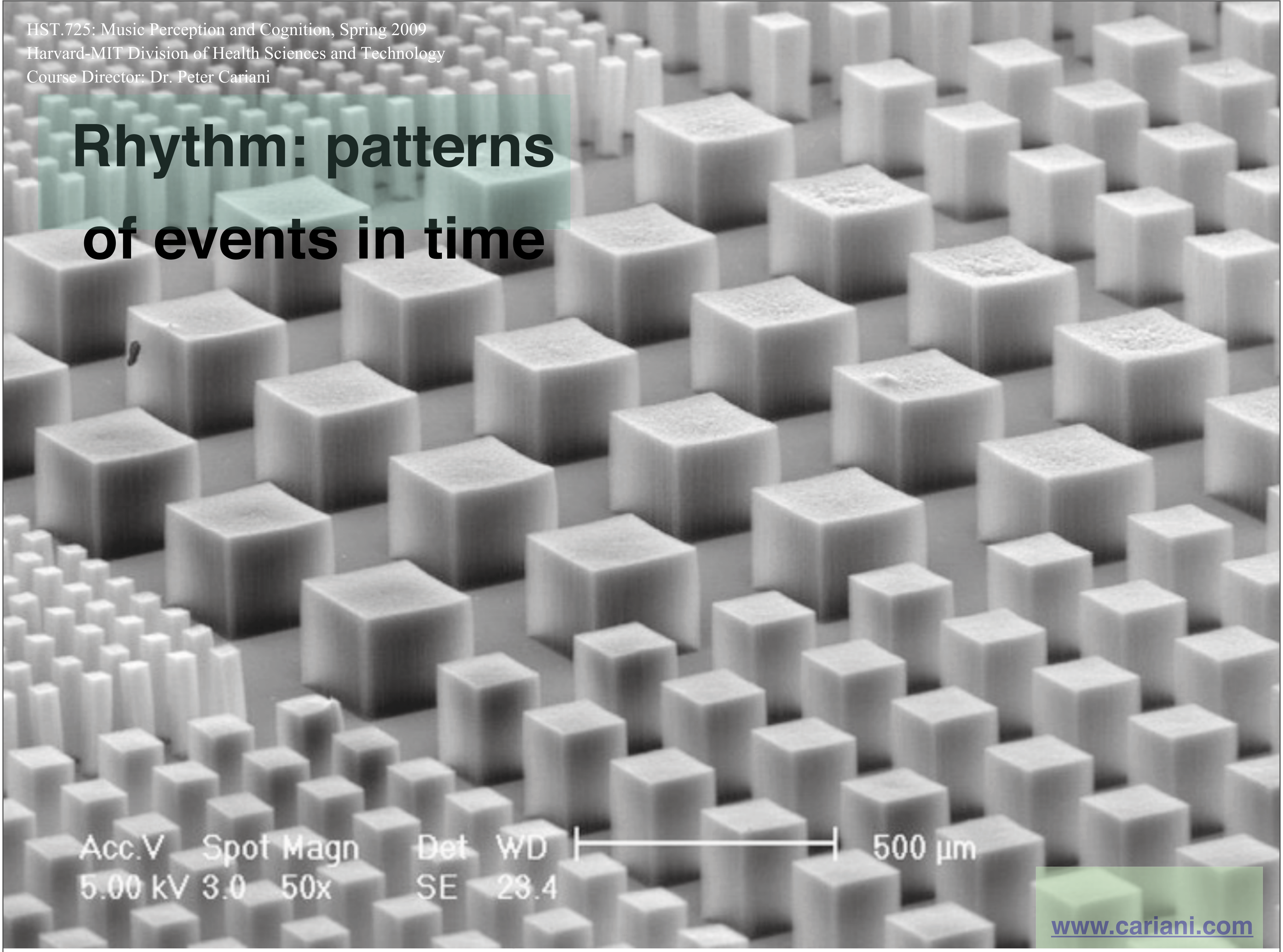
HST.725: Music Perception and Cognition, Spring 2009
Harvard-MIT Division of Health Sciences and Technology
Course Director: Dr. Peter Cariani

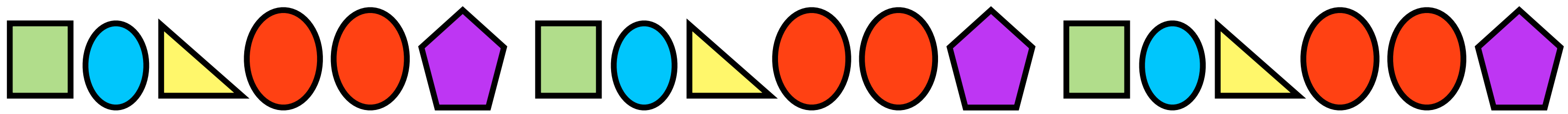
Rhythm: patterns of events in time



Thursday, May 14, 2009

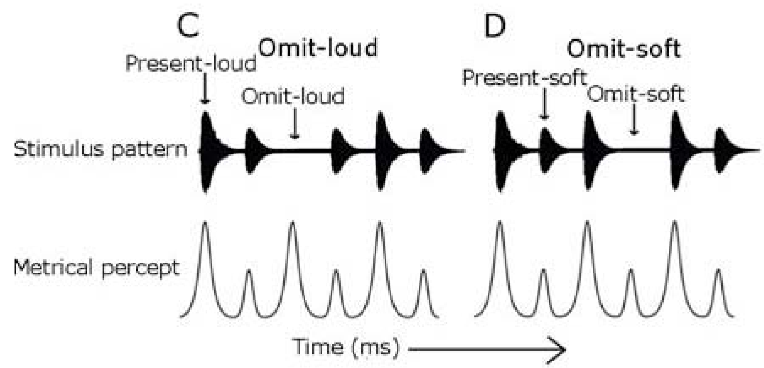
1. Rhythmic pattern induction & expectation

chunking of repeating patterns



2. Meter --

the inferred metrical grid



Source: Snyder, J. S., and E. W. Large. "Gamma-band Activity Reflects the Metric Structure of Rhythmic Tone Sequences." *Cog Brain Res* 24 (2005): 117-126. Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

3. The Time Sense

Image of Salvador Dali's painting "The Persistence of Memory" removed due to copyright restrictions.
See http://en.wikipedia.org/wiki/File:The_Persistence_of_Memory.jpg

Rhythm: patterns of events in time

What is rhythm? Perceived patterns of events in time

What constitutes an event? What makes events salient (accented)?

How many individual events can we distinguish (< 12/sec)?

Auditory sense and the time sense (supramodal)

- **Perception of duration, weber fractions for time**

Rhythmic pattern induction & expectation

- **Rhythmic pattern invariance w. respect to tempo**

Meter (regular underlying grid of accented/nonaccented events)

Rhythmic hierarchies, rhythmic complexity

Small integer-ratios again: models (clock, oscillator, timing net)

Polyrhythms; analogy to polyphony

Interactions between melody & rhythm: accents

Rhythms: musical, body, and brain; kinesis

Music notation: time durations

Fig. 2.2 in Sethares, W. A. *Rhythm and Transforms*.
Springer, 2007. ISBN: 9781846286391. Preview in Google Books.

Tempo (absolute timescale, in beats/minute)

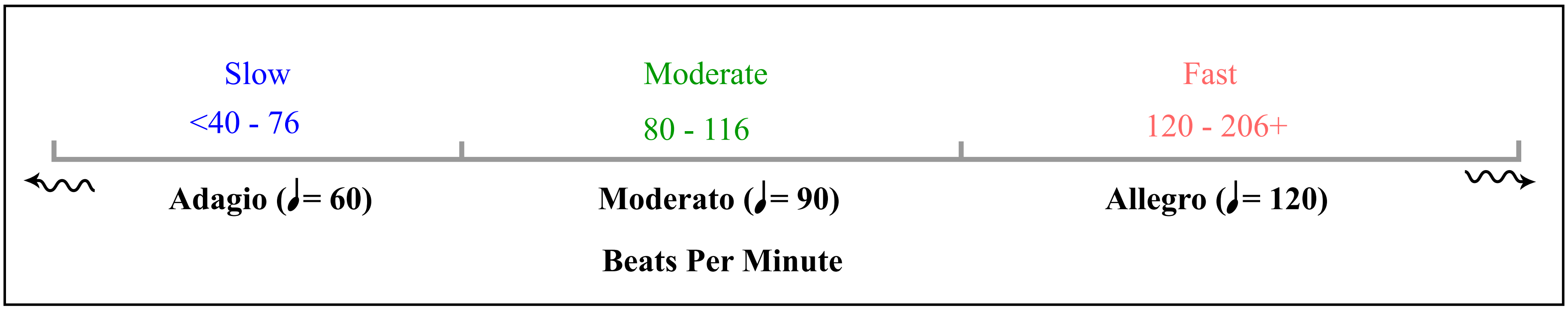


Figure by MIT OpenCourseWare.

Tempo

Ranges of events; intervals from 50 ms to 2 sec

Too short: events fuse

Too long: successive events don't cohere, interact

Pitch (> 30 Hz); infra-pitch (10-30 Hz); rhythm (< 10 Hz)

For a brisk tempo of 120 bpm, 2 Hz,

a quarter note is 500 msec (2 Hz)

an eighth note is 250 msec (4 Hz)

a sixteenth note is 125 ms (8 Hz)

a 32nd note is 62 ms (16 Hz)

Rhythm: general observations I

- **Different levels of temporal organization**
  - **Handel's basketball game analogy:**
- **Patterning**
  - **Rhythm: perception of grouping & ordering of events**
- **Perceptual groupings of events in time create perceived rhythmic patterns**
- **Temporal pattern expectancies create groupings**
  - **pattern repetition and**
  - **similar patterns of salient auditory contrasts (accents)**
- **Underlying temporal framework**
  - **(metrical grid, meter, tempo)**

Rhythm: recurring patterns of events in time

Every repeating pattern creates an expectancy of its continuation

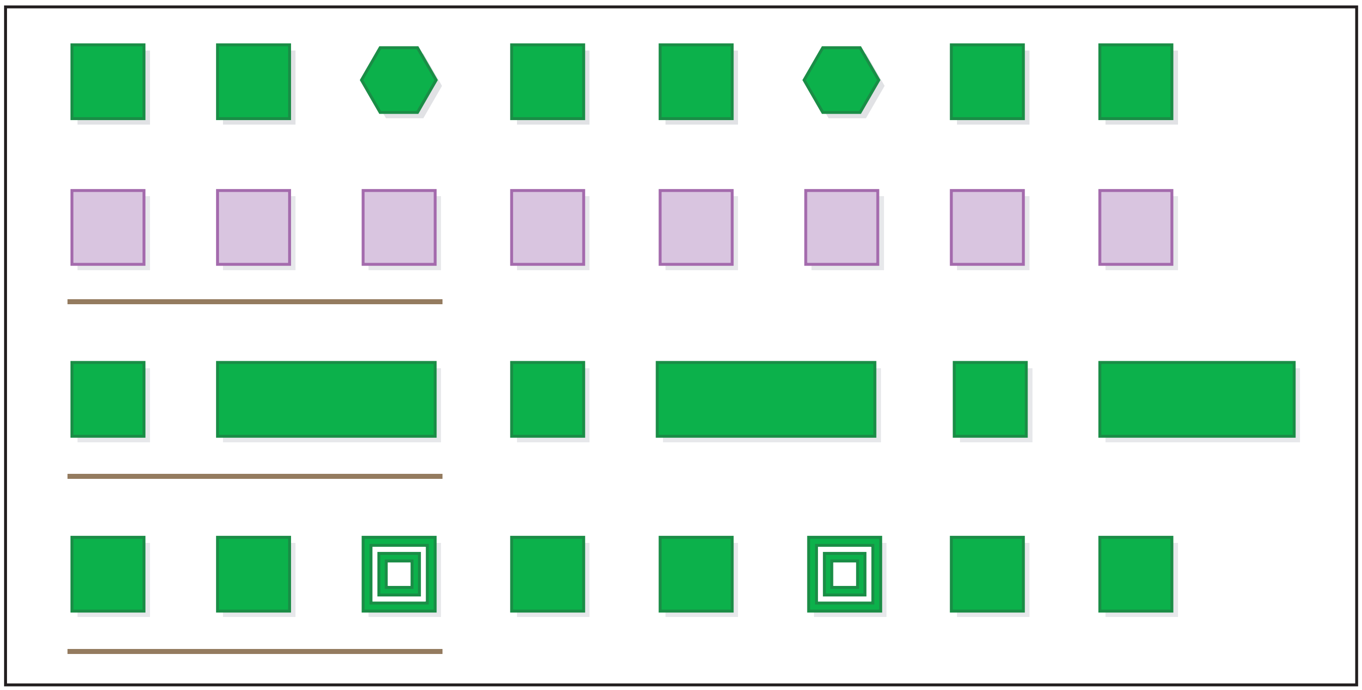


Figure by MIT OpenCourseWare.

Every repeating pattern creates an expectancy of its continuation

Further, there is a "chunking" of the repeating pattern (the invariant pattern becomes an object)

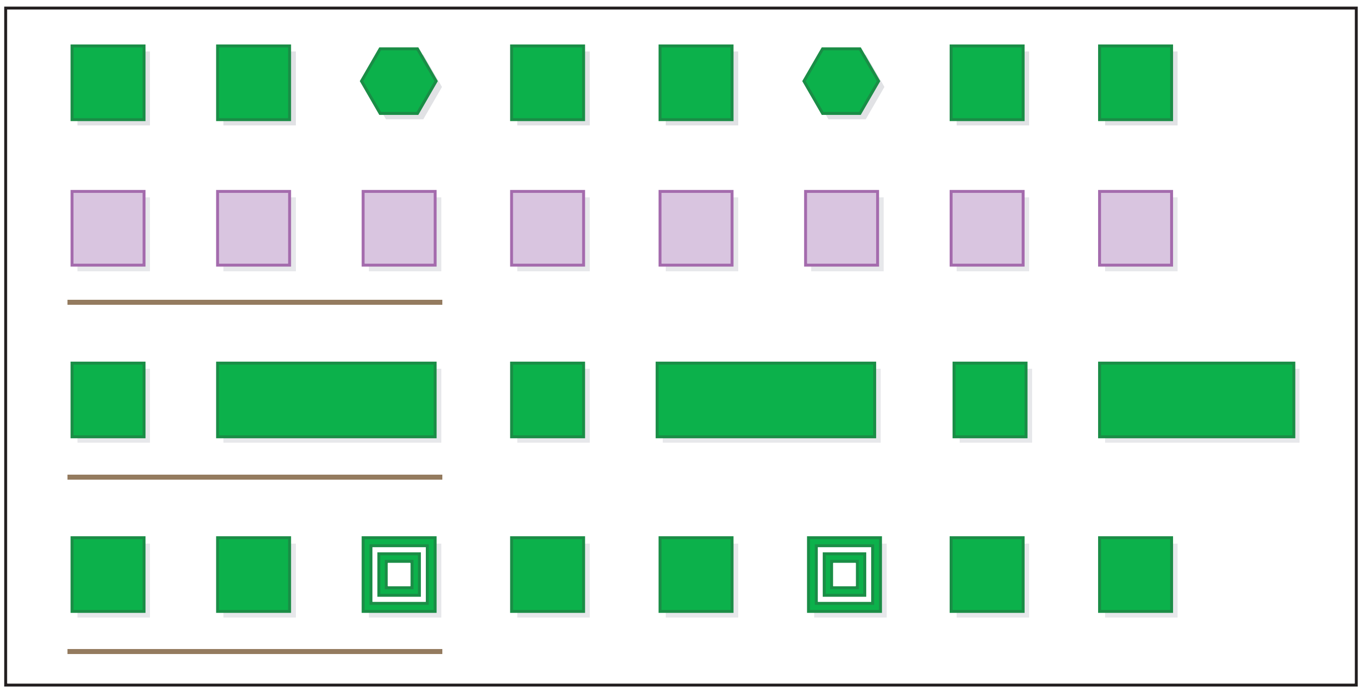


Figure by MIT OpenCourseWare.

Rhythm generation demonstration

- Repeating patterns of events
- Drum score representation
- Synthesizer

Acoustical grouping

(Snyder, Music & Memory)

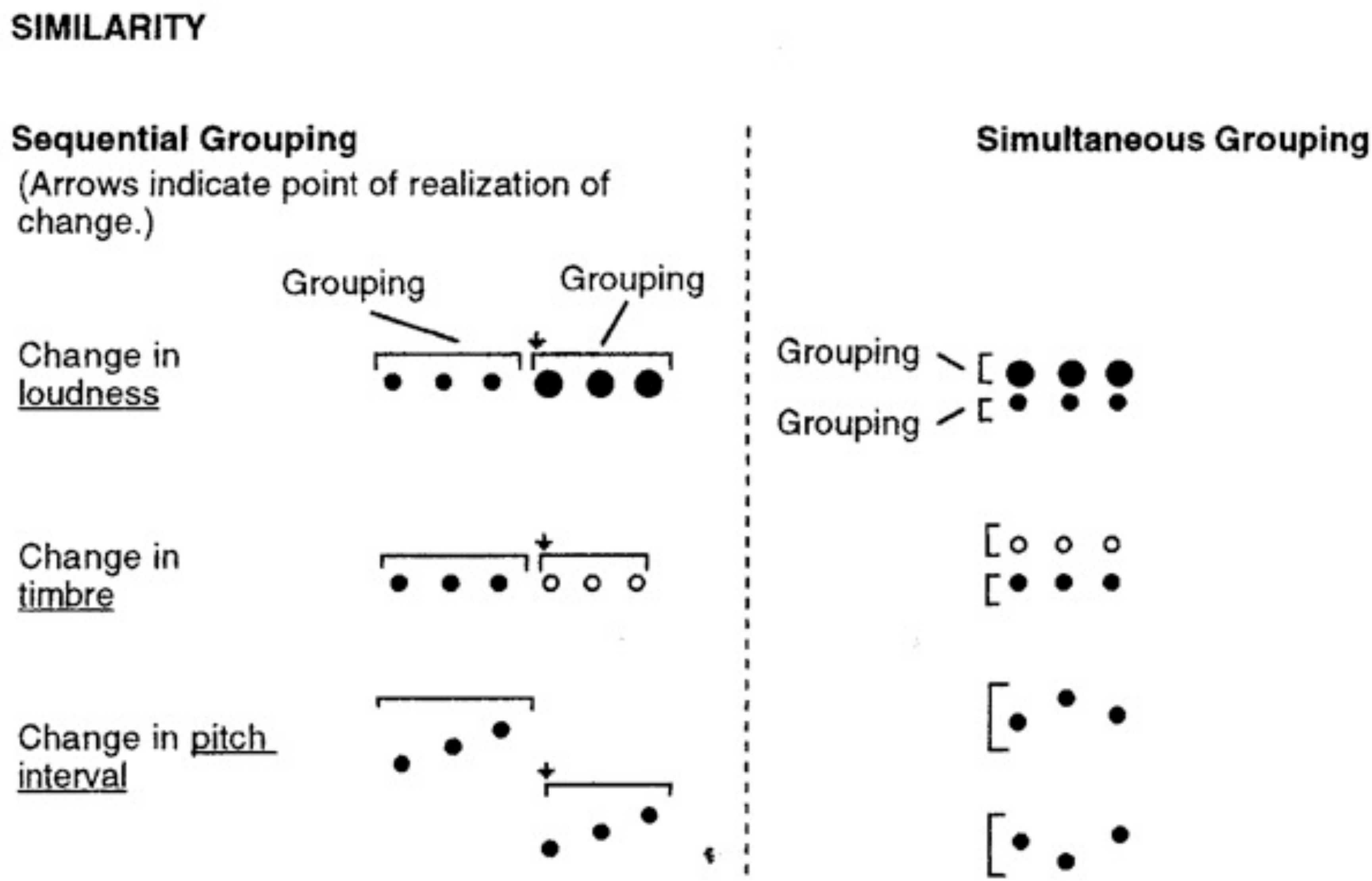


Figure 3.5
Acoustical grouping.

Source: Snyder, Bob. *Music and Memory.*
Cambridge, MA: MIT Press, 2000. Courtesy of MIT Press.
Used with permission.

Melodic & rhythmic grouping

(Snyder, Music & Memory)

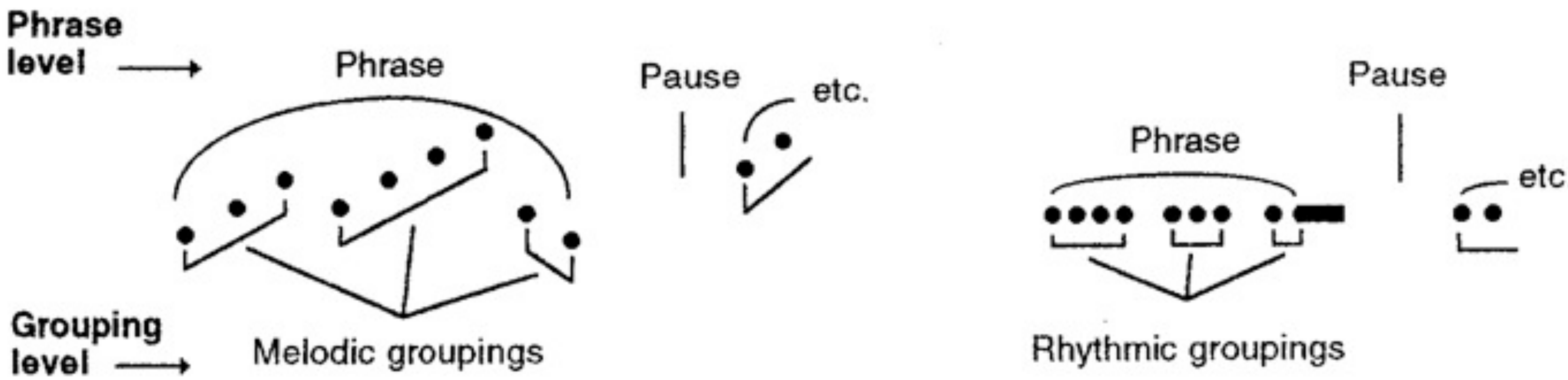


Figure 3.3
Melodic and rhythmic grouping.

Source: Snyder, Bob. *Music and Memory.*
Cambridge, MA: MIT Press, 2000. Courtesy of MIT Press.
Used with permission.

Temporal grouping

(Snyder, Music & Memory)

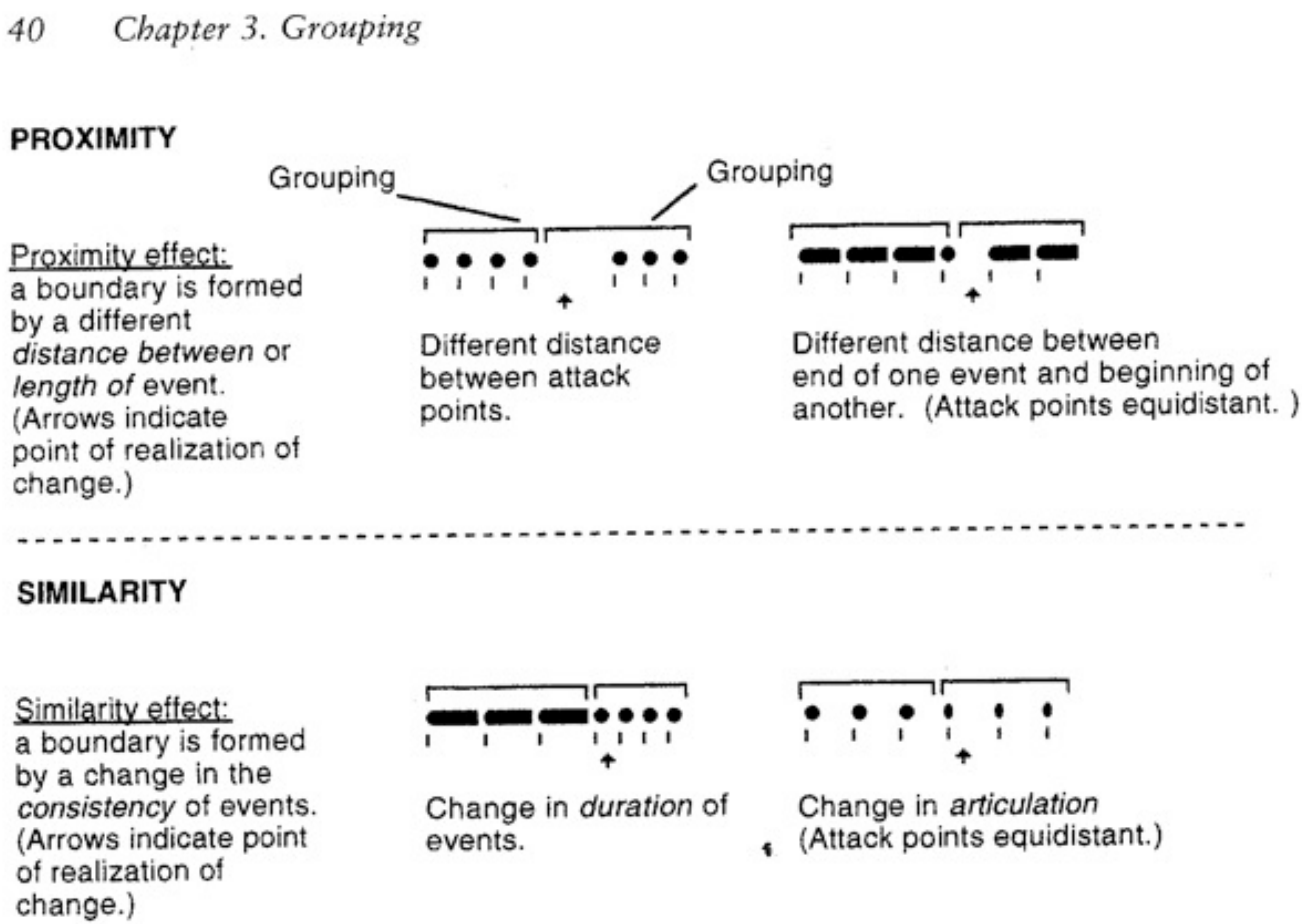


Figure 3.4
Temporal grouping.

Source: Snyder, Bob. *Music and Memory*. Cambridge, MA: MIT Press, 2000.

Repetition of a rhythmic pattern establishes the pattern

Image removed due to copyright restrictions.

a) Two measure rhythmic pattern.

b) Complete 2-bar pattern, followed by a repetition of the complete pattern.

c) Complete 2-bar pattern, followed by two repetitions of the 2nd measure.

d) Complete 2-bar pattern, followed by two repetitions of the 2nd measure in reverse.

e) Complete 2-bar pattern; unique 3rd measure, and then a repetition of the 2nd measure.

Music Theory,

Necklace notation: cyclical repeating patterns

Fig. 2.6 in Sethares, W. A. *Rhythm and Transforms*.
Springer, 2007. ISBN: 9781846286391.
Preview in Google Books.

Necklace notation: cyclical repeating patterns

Fig. 2.4 in Sethares, W. A. *Rhythm and Transforms*. Springer, 2007. ISBN: 9781846286391. Preview in Google Books.

see Sethares, 2007. Necklace notation: Safi al-Din al-Urmawi 13th c. Bagdad *Book of Cycles*

Necklace notation: cyclical repeating patterns

Fig. 2.5 in Sethares, W. A. *Rhythm and Transforms*. Springer, 2007. ISBN: 9781846286391. Preview in Google Books.

Sethares, 2007

Memory processes generate musical context

Tonality induction -- repetition of particular notes & sets of harmonics that establishes a tonal expectation through which all subsequent incoming tonal patterns are processed -- establishment of the tonic

Rhythmic induction -- repetition of patterns of accented and unaccented events that establishes a temporal pattern of expectation for subsequent events

Both kinds of induction operate on similarities and contrasts between previous and subsequent sounds & events

OLD + NEW heuristic:

1) OLD incoming patterns similar to previous ones build up the images of previous ones, confirm + strengthen expectations, create relaxation

2) NEW different patterns create contrasts that violate expectations established from previous inputs, create tension

3) degree of contrast (distance in perceptual space) determines the degree of tension created/resolved

Hierarchy & time order (Snyder, Music & Memory, MIT Press, 2000)

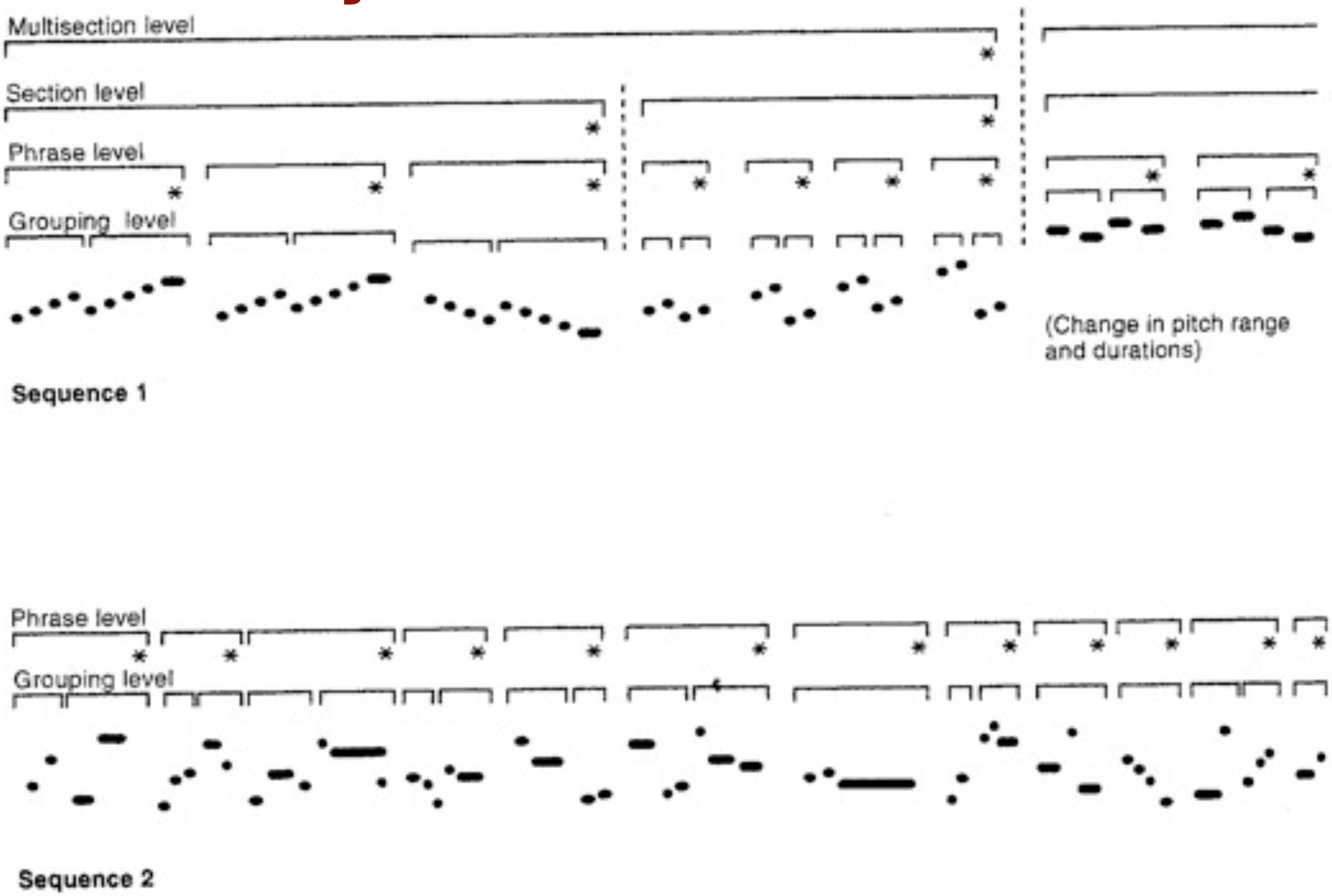
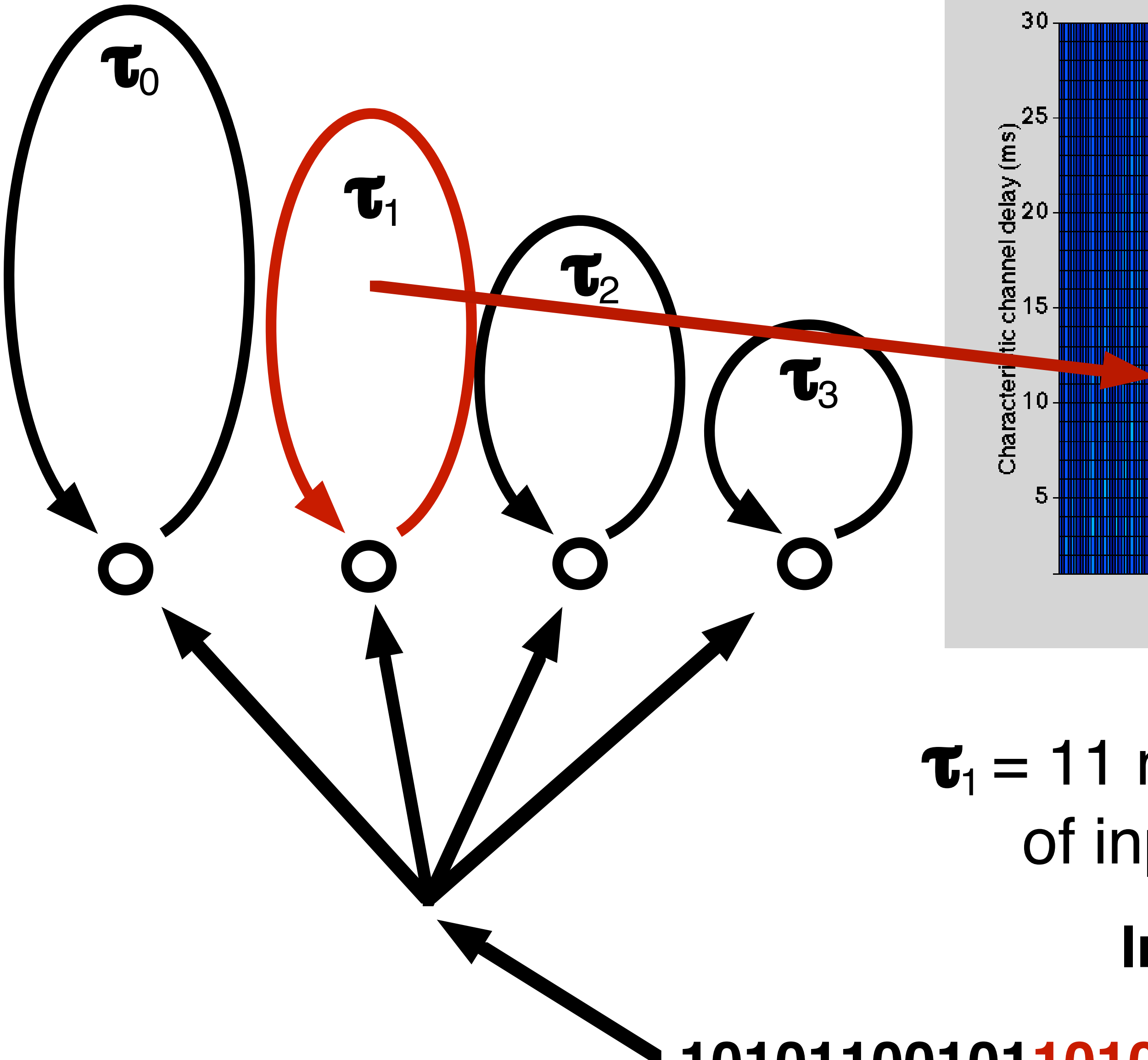
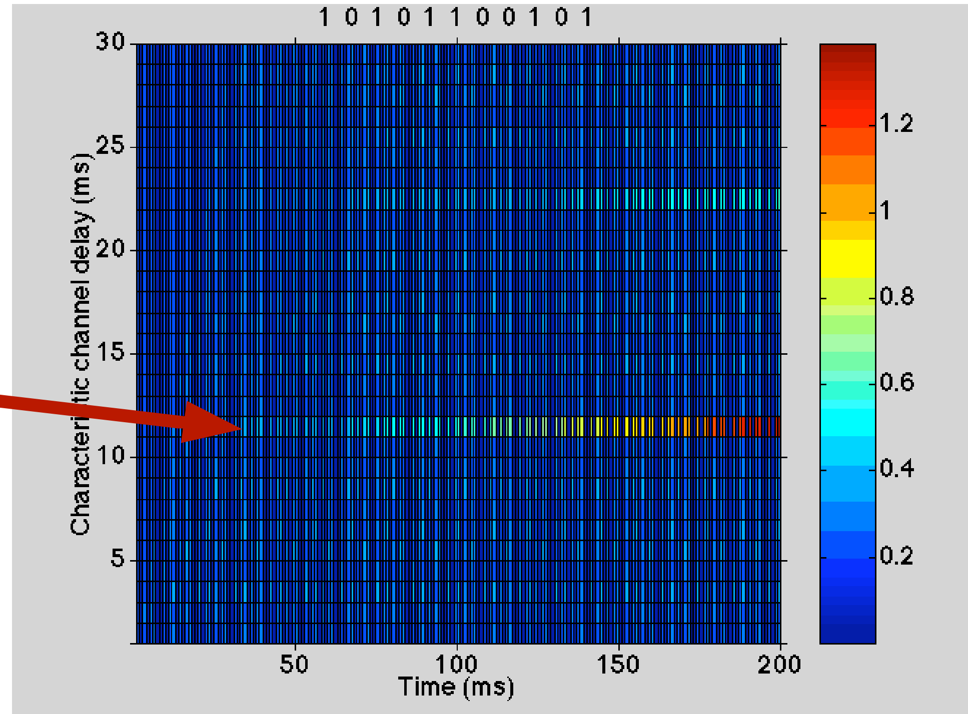


Figure 13.2
Hierarchy and time order. These diagrams represent a highly simplified representation of two ways of structuring time-ordered sequences of musical events. Both sequences have the same number of events. Complete chunks at various levels are represented by horizontal brackets; higher-level chunking boundaries, by dashed vertical lines; and cues, by asterisks.

Detection of arbitrary periodic patterns

Periodic patterns invariably build up in delay loops whose recurrence times equals the period of the pattern and its multiples.





τ_1 = 11 ms = recurrence time of input pattern10101100101

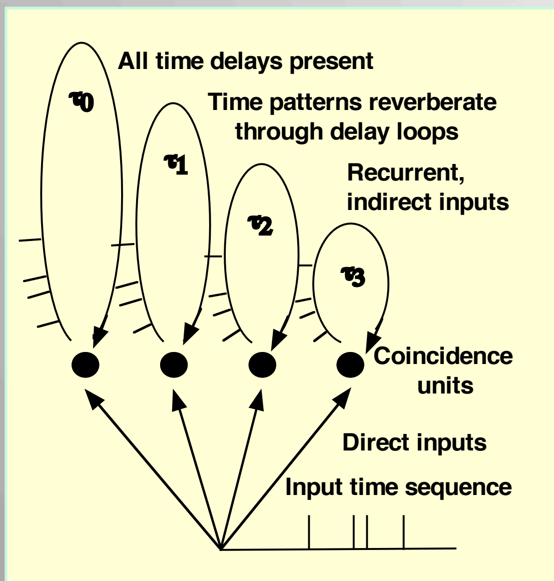
Input pattern

10101100101**10101100101****101011001011010...**

Temporal coding of rhythm

Stimulus-driven temporal patterns of spikes encode event structures

- Exist at the cortical level for periodicities < 15 Hz
- Can directly encode rhythmic patterns
- Amenable to processing via recurrent timing nets (RTNs)
- Chunk recurrent patterns of events to create rhythmic expectancies



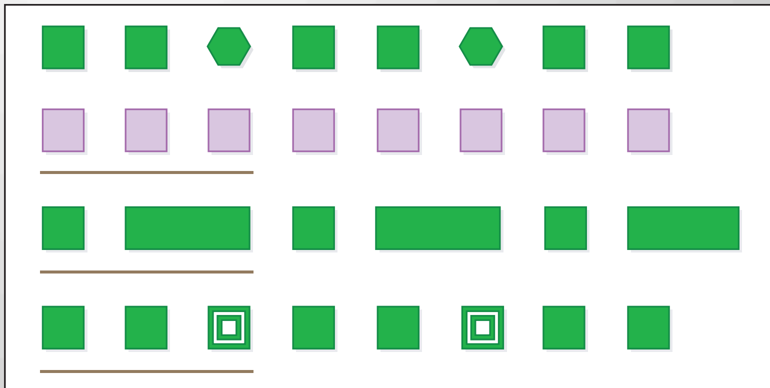


Figure by MIT OpenCourseWare.

Δ quality

no Δ

Δ pitch

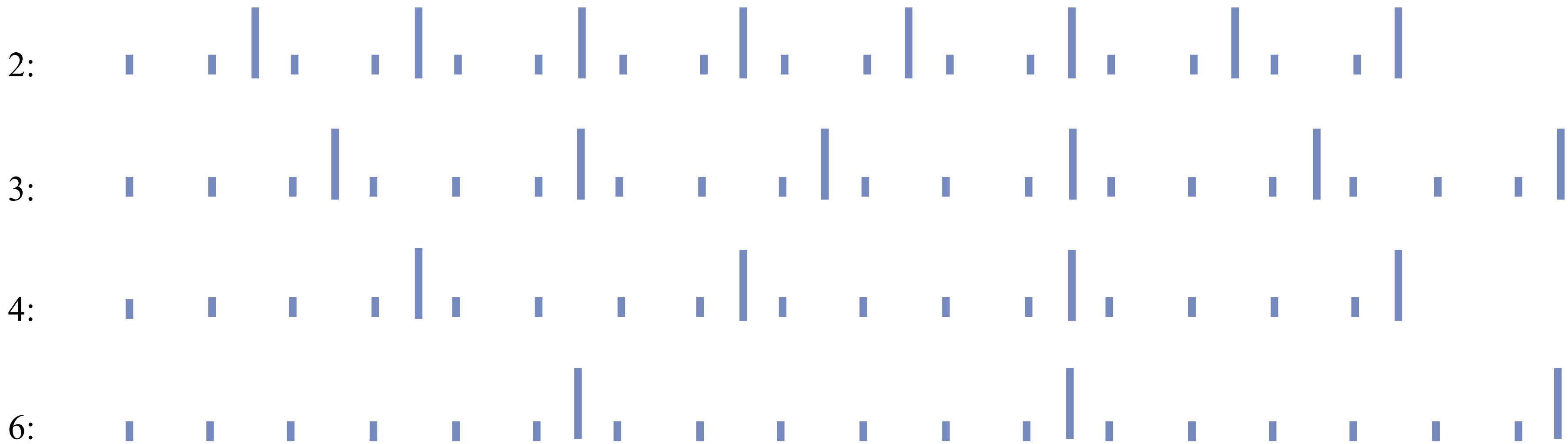
Δ timbre

Δ duration

In addition to rhythmic patterning, we seem to infer an underlying metrical grid to the stream of events (e.g. inferences that allow us to tap our fingers or toes to a beat or to keep time with the music)

This perception of an underlying metrical order is important for coordination of musicians playing in groups.

Meter serves as a temporal context that is somewhat independent of individual events (somewhat like the tonic vis-a-vis melody)



Meter and Accent

The recurrent groups of pulsations are called *meters*: for example, duple meter, triple meter, and quadruple meter. The beats within the measures are counted and accented:

2: <u>one</u>, two | <u>one</u>, two |
3: <u>one</u>, two, three | <u>one</u>, two, three |
4: <u>one</u>, two, th<u>re</u>e, four | <u>one</u>, two, th<u>re</u>e, four |
6: <u>one</u>, two, three, <u>four</u>, five, six |

Figure by MIT OpenCourseWare.

Meter (e.g. 4 pulses per measure, accent)

Definition: The number of pulses between the more or less regularly recurring accents

(Cooper and Meyer , 1960).

Most authors define meter similarly, as somehow dependent upon (and perhaps contributing to) patterns of accent.

Zuckerkandl (1956), however, views meter as a series of "waves" that carry the listener continuously from one beat to the next. For him, they result not from accentual patterns but simply and naturally from the constant demarcation of equal time intervals.

http://www.music.indiana.edu/som/courses/rhythm/illustrations

Pulse & the metrical grid (meter)

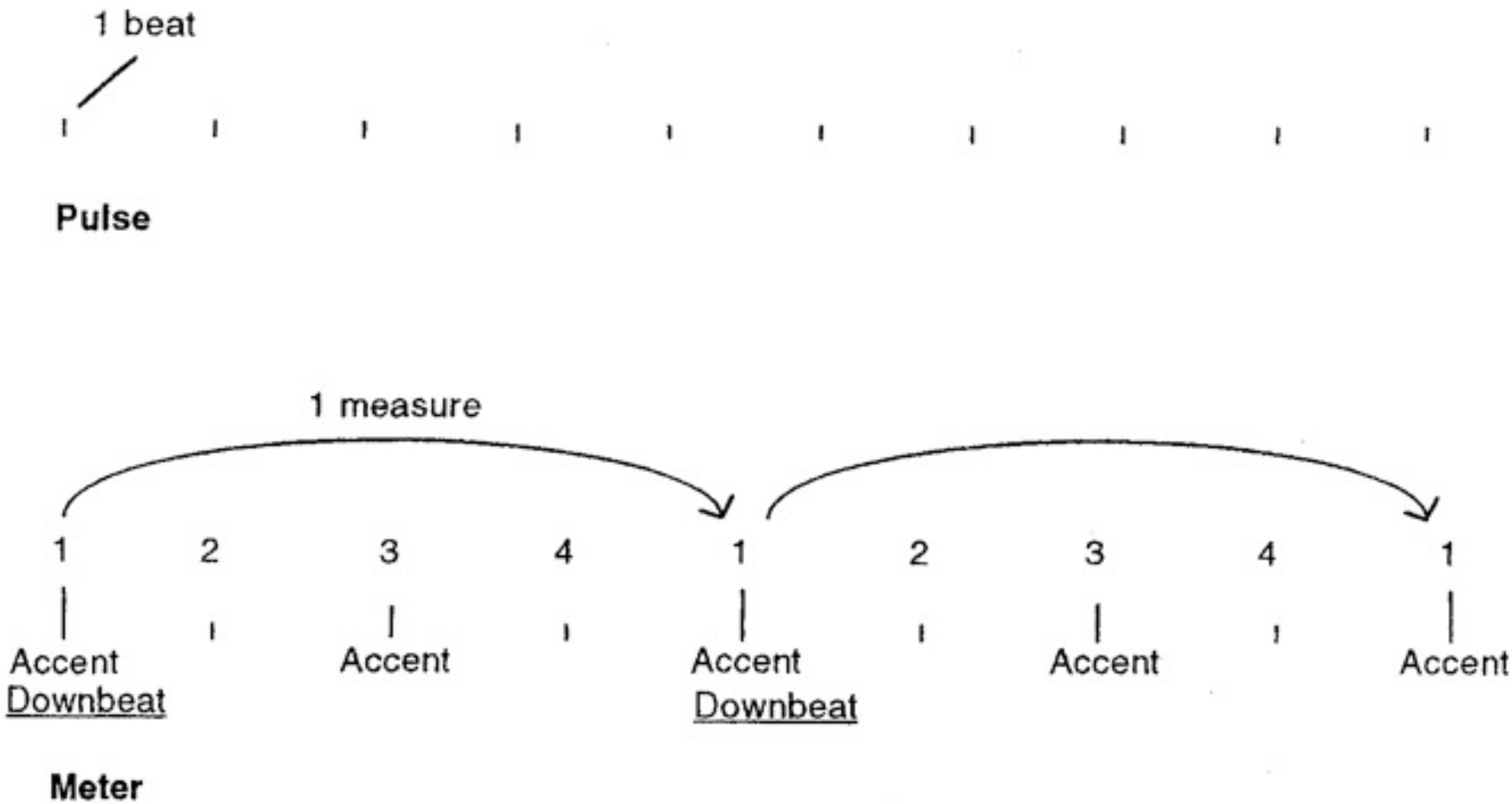


Figure 12.5
Pulse and meter.

Source: Snyder, Bob. *Music and Memory.* Cambridge, MA: MIT Press, 2000. Courtesy of MIT Press. Used with permission.

Pulse

- **Definition:** A series of regularly recurring, precisely equivalent stimuli (Cooper and Meyer , 1960).

- According to Parncutt (1987), a chain of events, roughly equally spaced in time.

http://www.music.indiana.edu/som/courses/rhythm/illustrations

Visual grouping

Dember & Bagwell, 1985, A history of perception, Topics in the History of Psychology, Kimble & Schlesinger, eds.

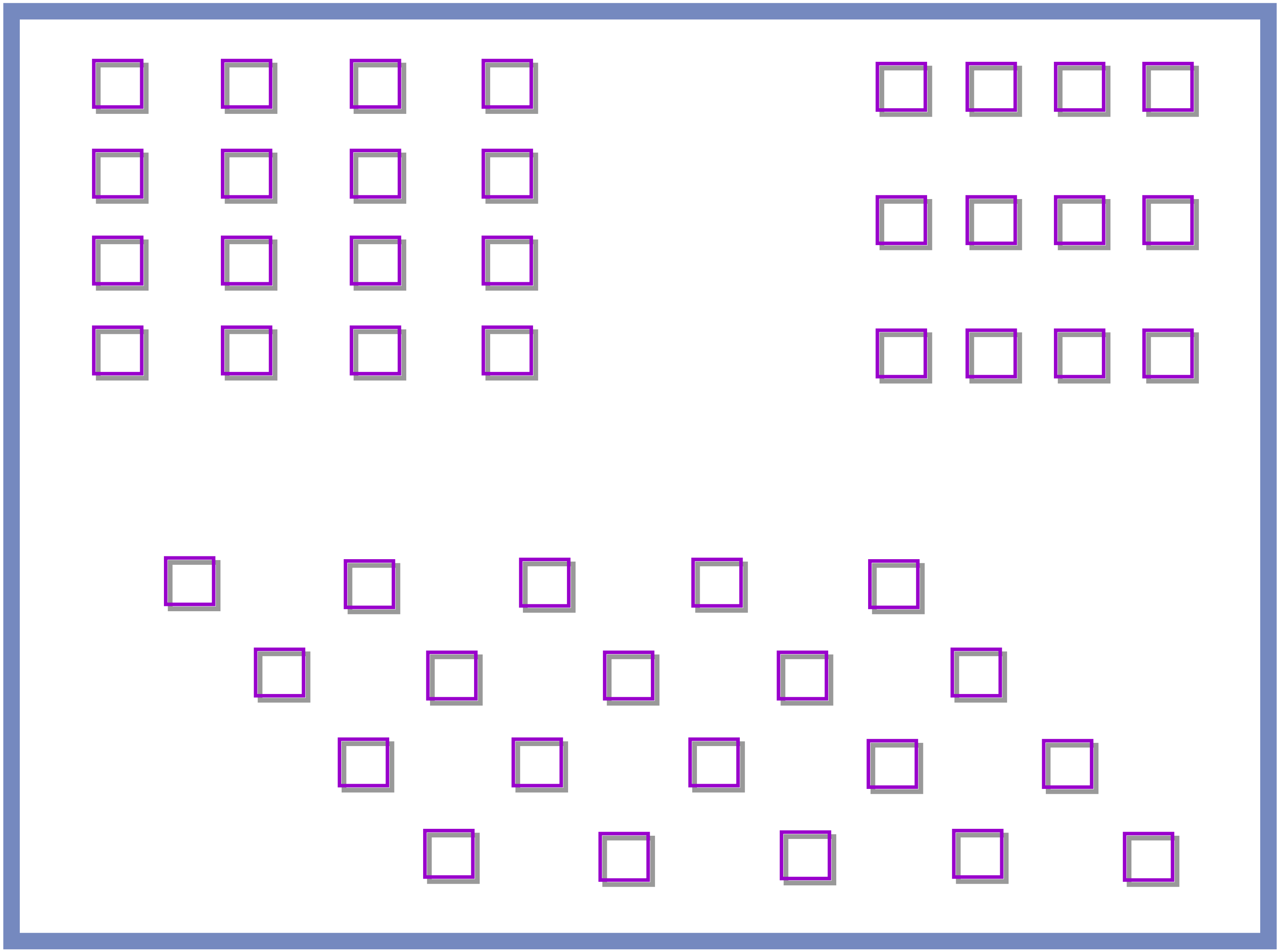


Figure by MIT OpenCourseWare.

Accent causes grouping which determines perceived rhythmic pattern

Rhythm is a perceptual attribute

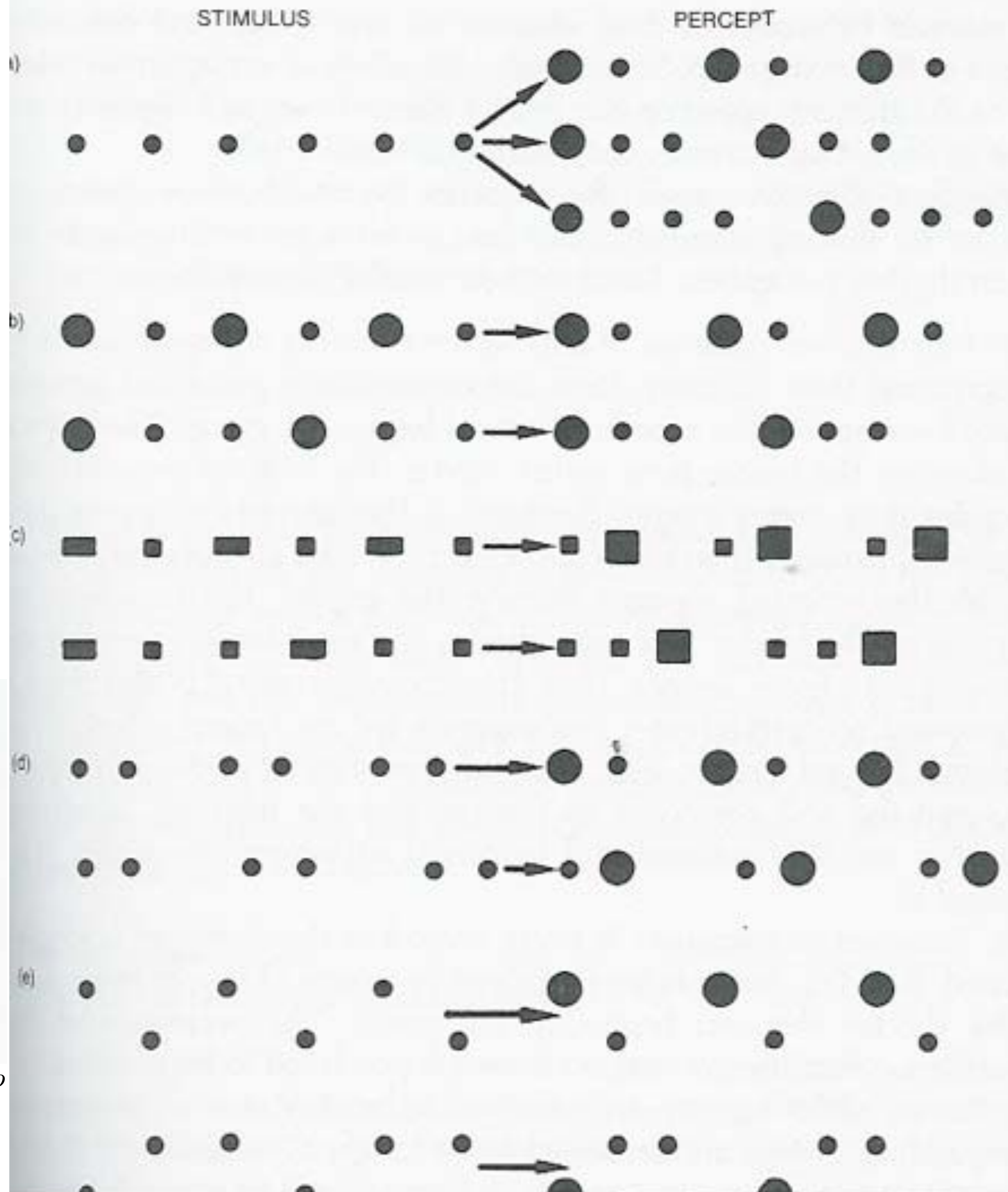


Figure 11.1
"Subjective" rhythm. A series of equally timed elements (i.e., equal temporal intervals between the onset of successive identical elements) is perceived as rhythmical. A series of identical elements, as in (*a*), is perceived to form groups of 2, 3, or 4 elements. The initial element of each group is perceived to be accented (represented by a bigger filled circle), and the time intervals between elements do not appear equal. If every second or third element is more intense, as in (*b*), the elements are perceived to form groups so that the more intense elements begin each group and there appear to be longer intervals between groups. If every second or third element is longer, as in (*c*), the elements are perceived to form groups so that the longer duration elements are the last elements of each group, the longer duration elements appear accented, and there appear to be longer intervals between groups. If every second interval between two elements is increased so that the elements form groups temporally, as in (*d*), then the first elements of each group appears accented if the longer interval is slightly greater than the other intervals, but the last element of each group appears accented if the longer interval is much greater than the other interval. If the elements are different frequencies, as in (*e*), then the elements are perceived to form groups so that the higher-pitch element begins each group and appears accented, and the interval between groups appears longer. If one note occurs less often, it may appear to be accented and begin each group.

Source: Handel, S. Listening: *An Introduction to the Perception of Auditory Events*. Cambridge, MA: MIT Press, 1989.

Factors that cause events to be accented: auditory contrast, salience

- note duration
- note intensity
- sharpness of attack
- duration of silence preceding it
- contrast: melodic contour/ pitch change
- regularity of timing (accented beats are "on time")
- position within a metrical organization
- According to Cooper & Meyer (1960), an accented tone must be set off from the rest of the series in some way (i.e. a salient contrast)

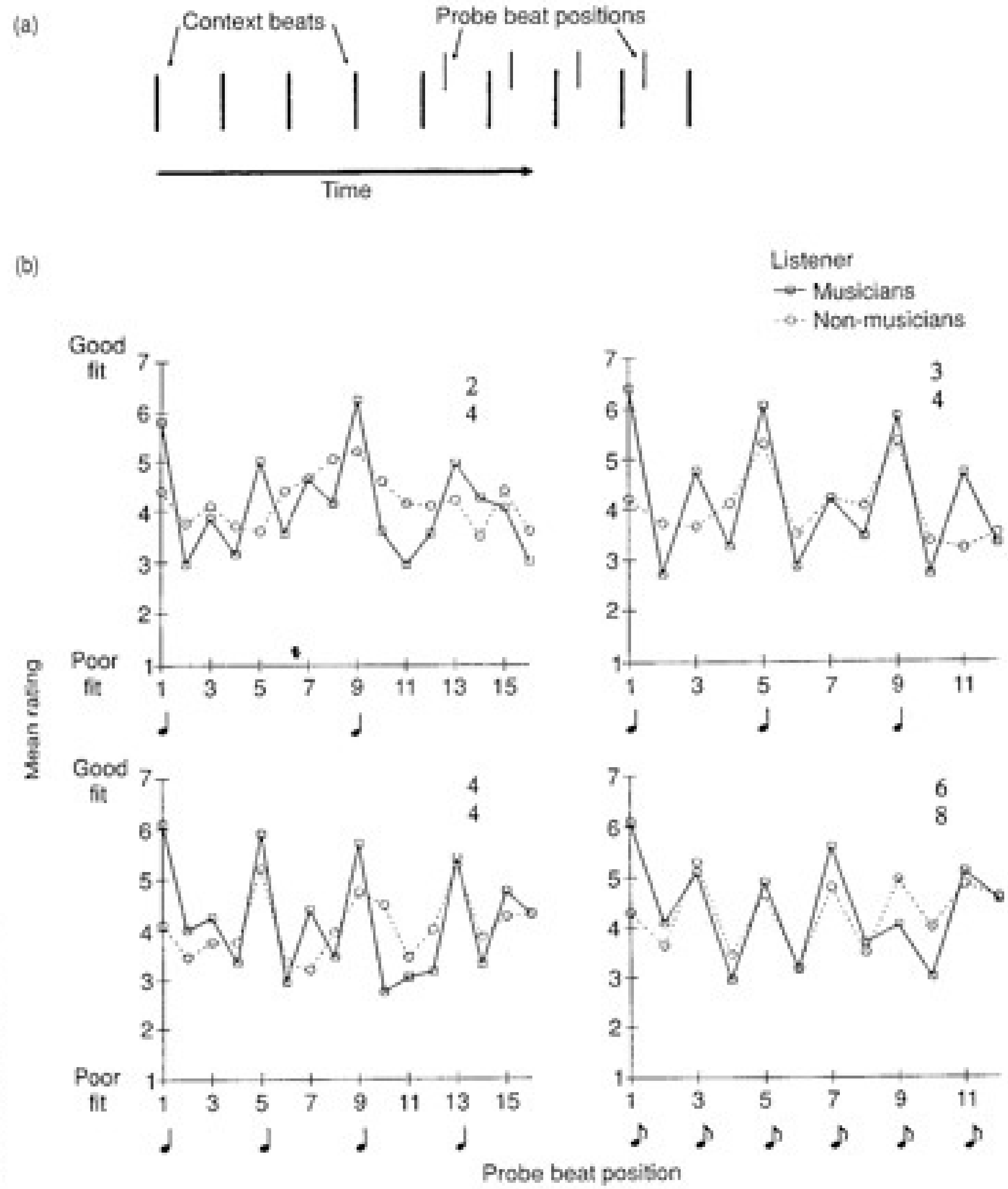
Expressive timing & expectation

expressive timing Definition:

Music psychologists' term for the deviations from a strictly uniform pulse that occur in live performance. These deviations most commonly occur near the ends of phrases and other grouping units. See Todd (1985).

http://www.music.indiana.edu/som/courses/rhythm/illustrations

Meter and beat induction



Source: Palmer, C., and C. L. Krumhansl.
"Mental representations for musical meter."
J Exp Psychol Hum Percept Perform 16, no. 4 (Nov 1990): 728-741.
Courtesy of the American Psychological Association.

- *From* Thinking in Sound

rhythmic, metrical dissonance

- **metrical dissonance Definition:** According to Krebs (1987), a situation in which the pulses in two metrical levels are not well aligned, either because the duration of the pulses in one level is not an integral multiple or division of the duration of the pulses in the other level, or because the pulses in one level are displaced by some constant interval from those in the other level. See also Yeston's rhythmic dissonance .

http://www.music.indiana.edu/som/courses/rhythm/illustrations

Event-related potentials & violations of temporal expectation

(notes, chords, beats, words (phonetic, semantic), many other levels of expectation)

Photo and graph of EEG/ERP removed due to copyright restrictions.
See: http://www.musicianbrain.com/methods.php#methods

Available online at www.sciencedirect.com

Cognitive Brain Research 24 (2005) 117–126

www.elsevier.com/locate/cogbrainres

Research report

Gamma-band activity reflects the metric structure of rhythmic tone sequences

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Accepted 28 December 2004
Available online 17 February 2005

Abstract

Relatively little is known about the dynamics of auditory cortical rhythm processing using non-invasive methods, partly because resolving responses to events in patterns is difficult using long-latency auditory neuroelectric responses. We studied the relationship between short-latency gamma-band (20–60 Hz) activity (GBA) and the structure of rhythmic tone sequences. We show that induced (non-phase-locked) GBA predicts tone onsets and persists when expected tones are omitted. Evoked (phase-locked) GBA occurs in response to tone onsets with ~50 ms latency, and is strongly diminished during tone omissions. These properties of auditory GBA correspond with perception of meter in acoustic sequences and provide evidence for the dynamic allocation of attention to temporally structured auditory sequences.

Theme: Neural basis of behavior
Topic: Cognition

Keywords: Electroencephalography; Gamma-band activity; Rhythm perception; Music; Speech

Thursday, May 14, 2009

Snyder & Large experiments on beat induction

J.S. Snyder, E.W. Large / Cognitive Brain Research 24 (2005) 117–126 119

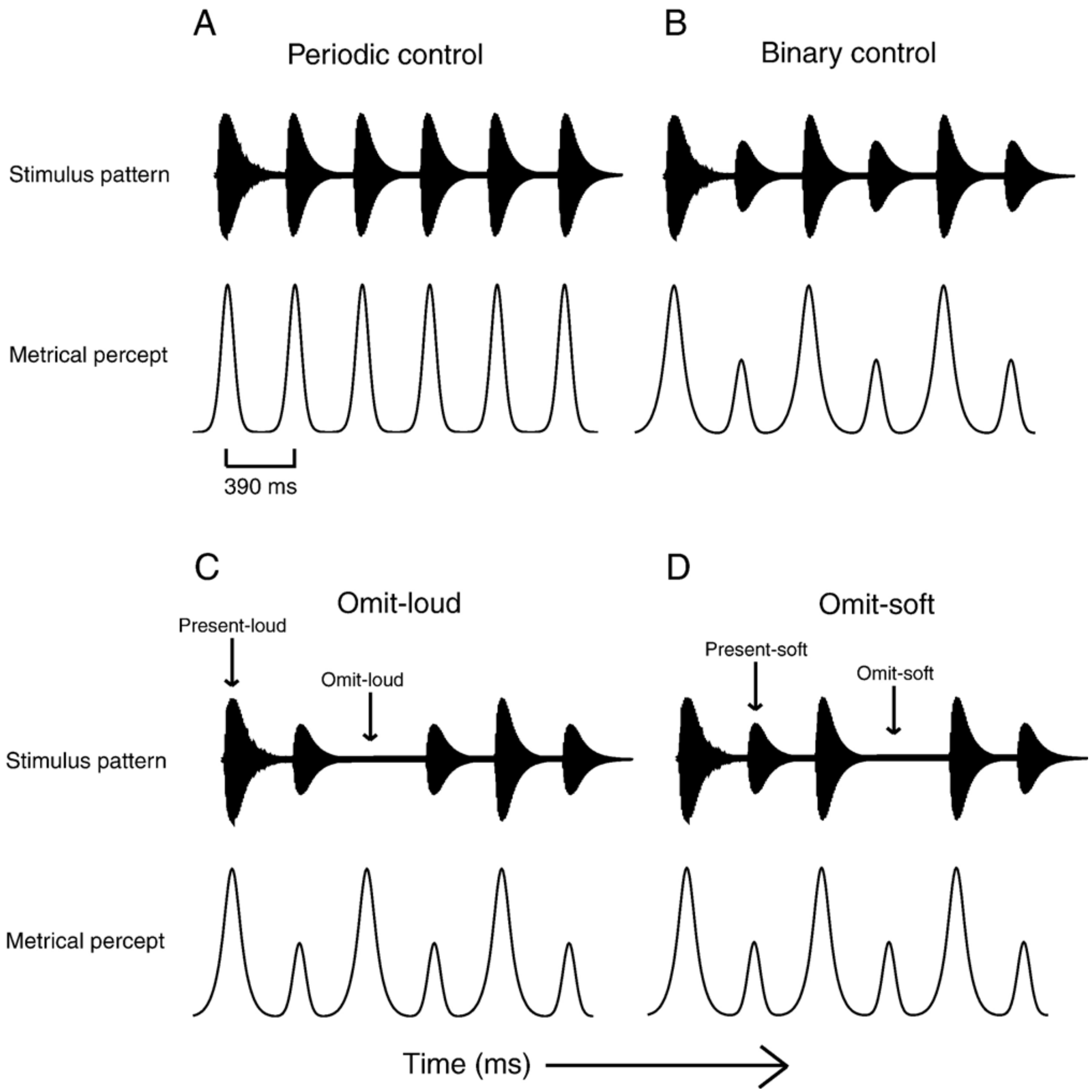
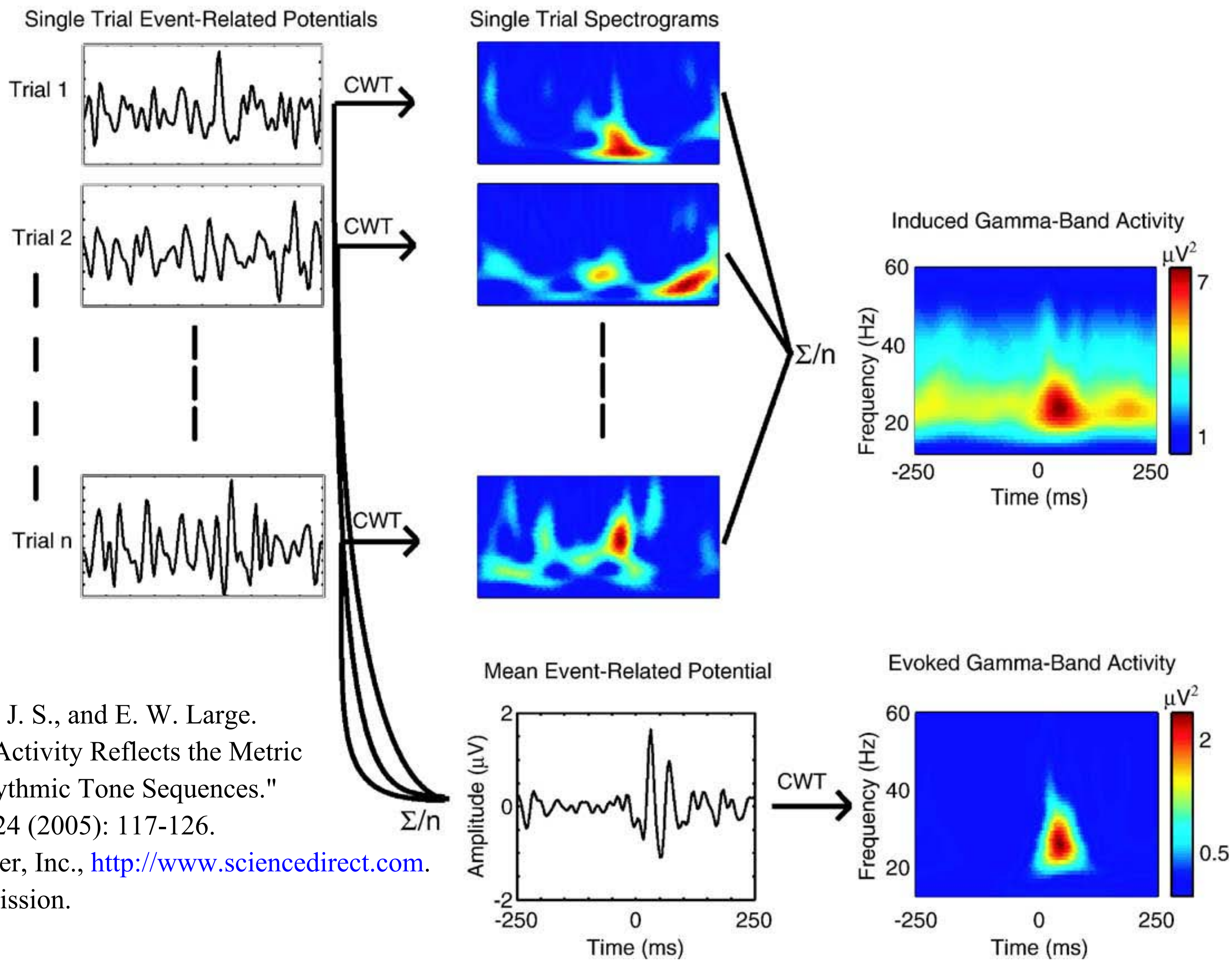


Fig. 1. Pure-tone (262 Hz, 50 ms duration) stimulus patterns are shown with inter-onset intervals of 390 ms (above) and schematized metrical accent representations (below). The periodic control condition consisted of isochronous tones designed to elicit a simple pulse perception (A). The binary control condition consisted of alternating loud and soft tones, designed to elicit a duple meter perception (B). The omit-loud condition consisted of the binary control pattern with missing loud tones on 30% of two-tone cycles (C). The omit-soft condition consisted of the binary control pattern with missing soft tones on 30% of two-tone cycles (D).



Source: Snyder, J. S., and E. W. Large. "Gamma-band Activity Reflects the Metric Structure of Rhythmic Tone Sequences." *Cog Brain Res* 24 (2005): 117-126. Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

Figure 2. Process to calculate evoked and gamma-band activity (GBA).

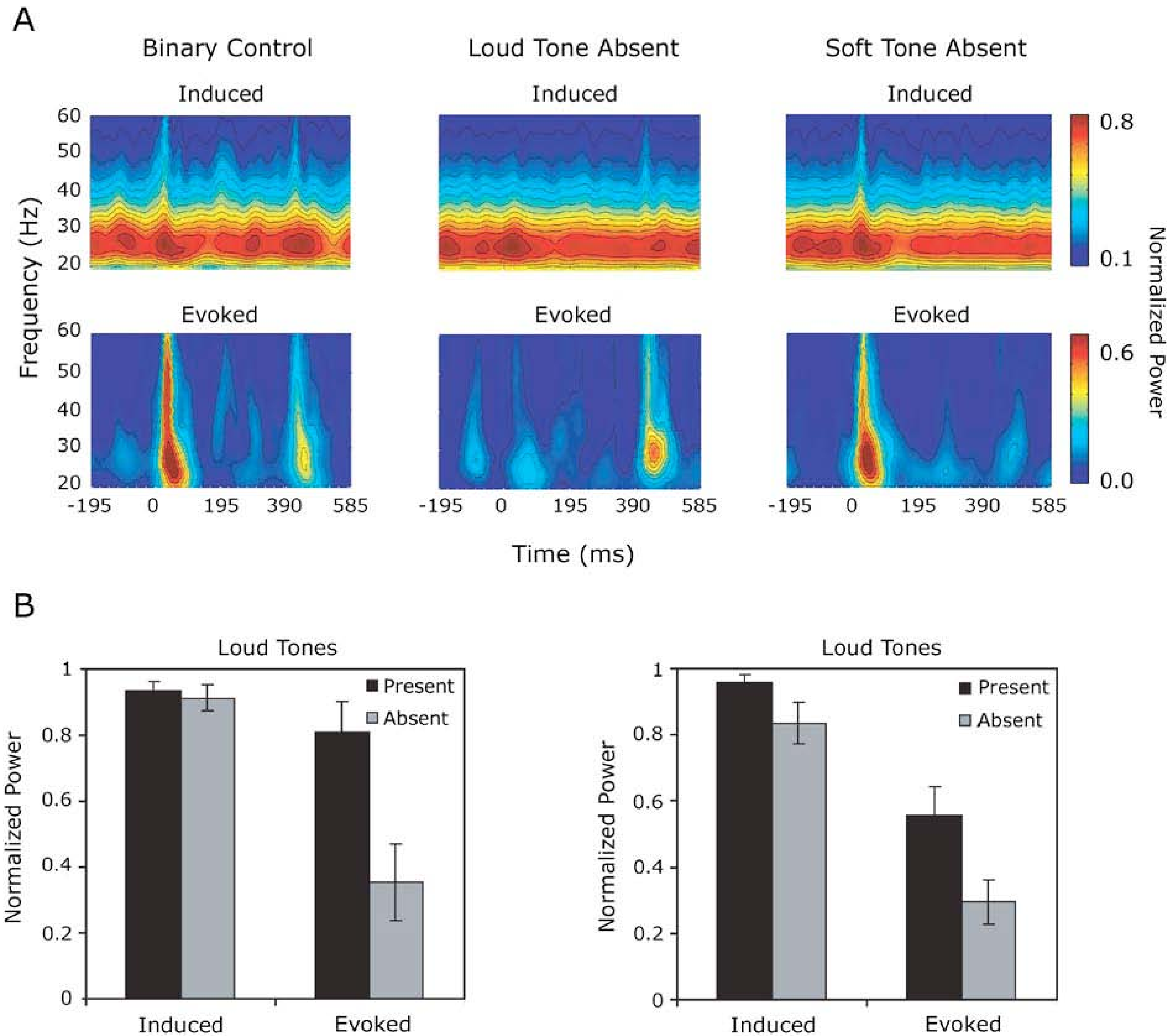
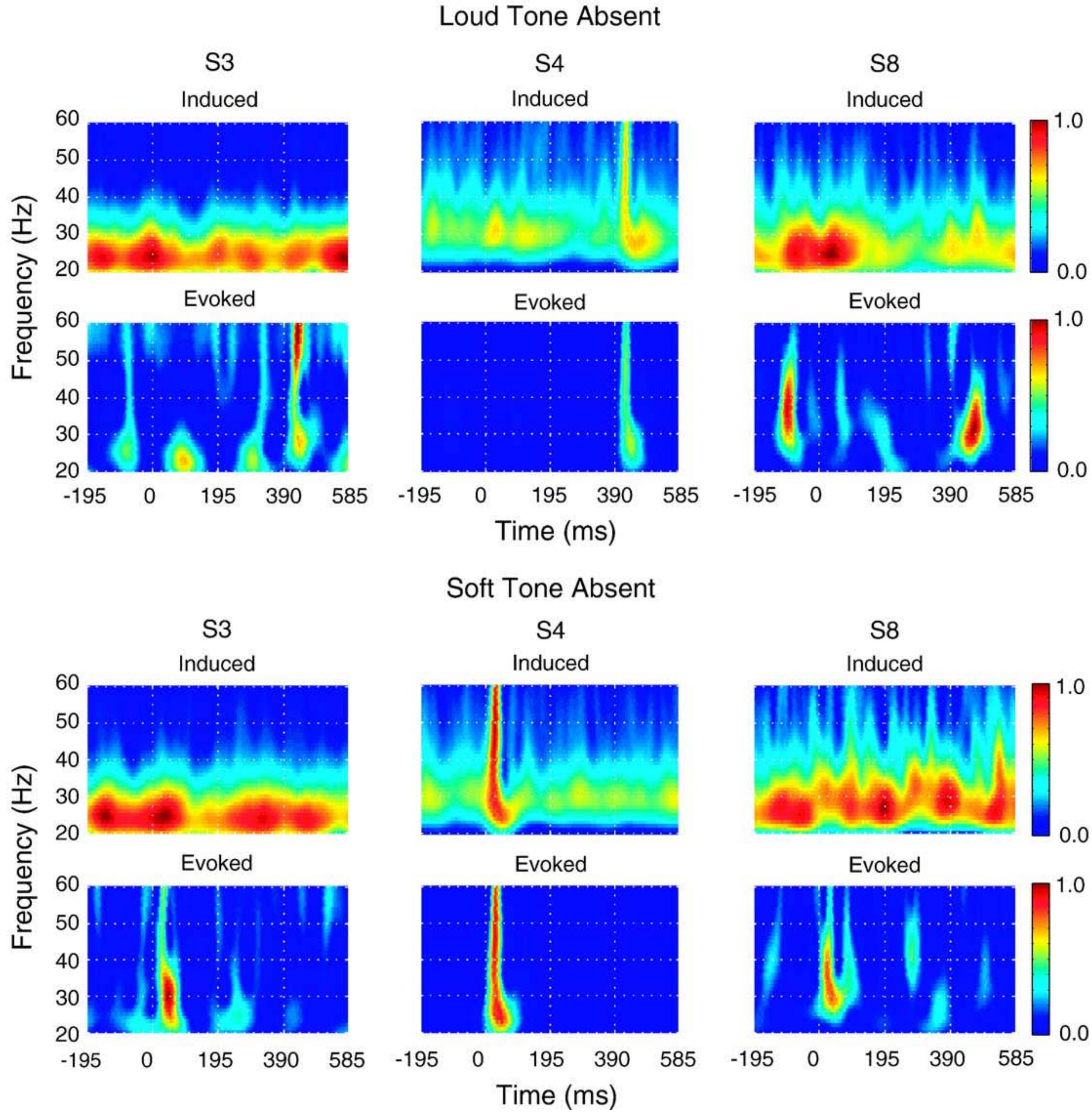


Figure 4. Courtesy of University of Finance and Management, Warsaw. Used with permission.

*(**a**) Time-frequency representation of the evoked and induced GBA results, averaged over all subjects. Tone onset occurs at zero and 390 ms. (**b**) Comparison of induced/evoked peak activity in the presence and absence of loud and soft tones.*



Source: Snyder, J. S., and E. W. Large. "Gamma-band Activity Reflects the Metric Structure of Rhythmic Tone Sequences." *Cog Brain Res* 24 (2005): 117-126.
Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

Figure 7. Tone omissions: induced and evoked GBA.

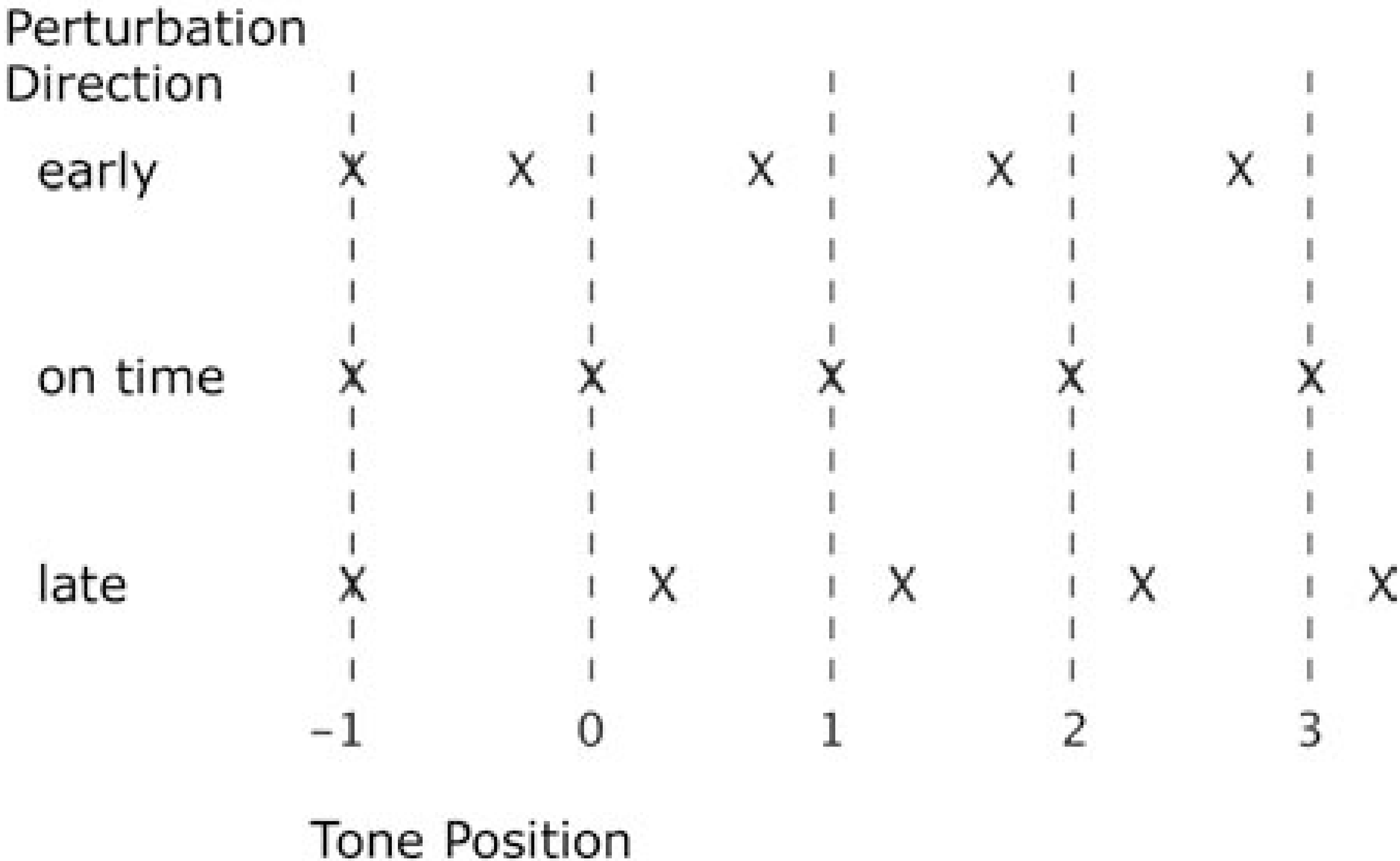


Figure 5.

Perturbed stimuli; 'x' represents tone onset.

Evoked GBA

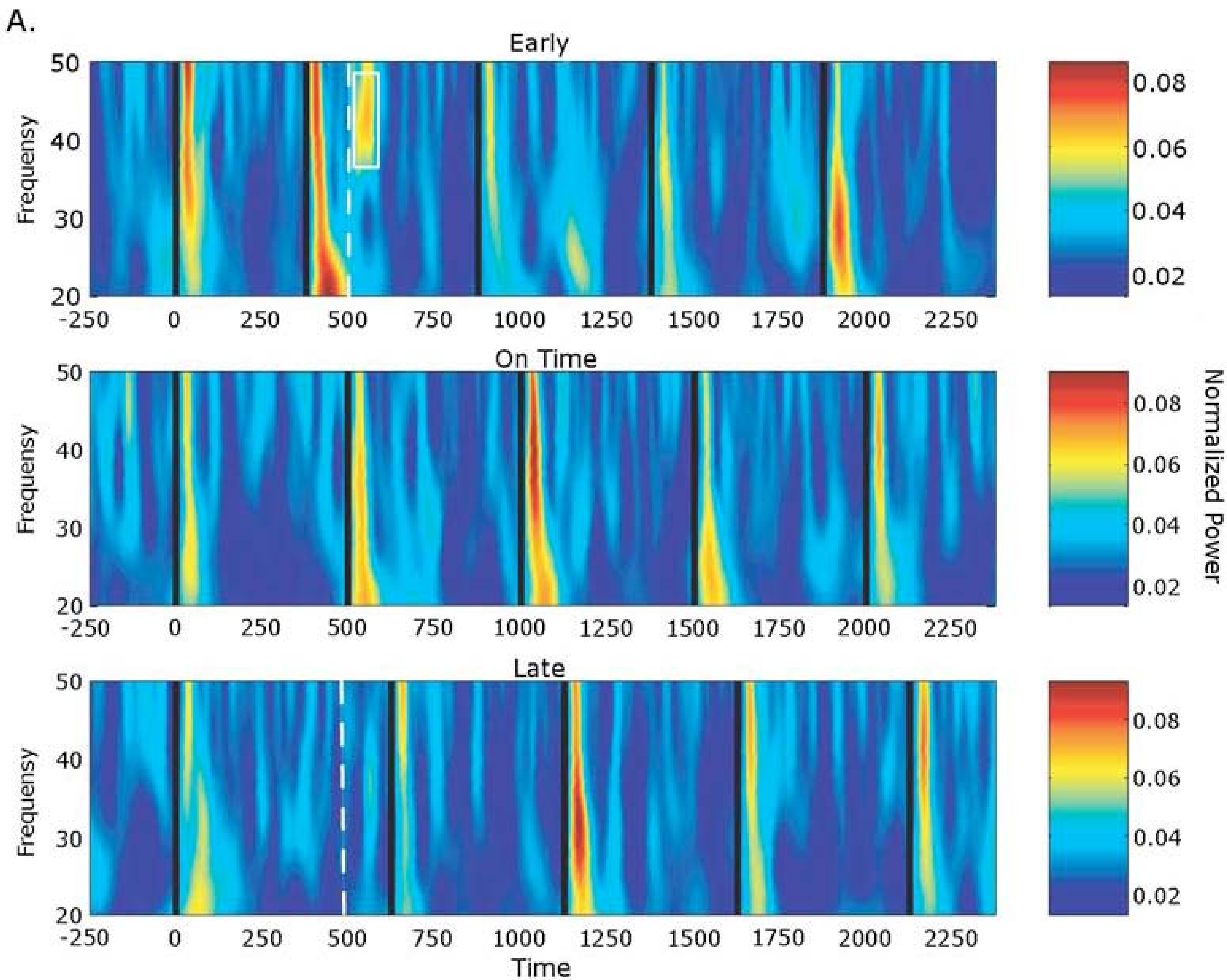


Figure 6.

Courtesy of University of Finance and Management, Warsaw. Used with permission.

*Time-frequency representation of the evoked and induced GBA in response to early, late, or on-time tones averaged over all subjects. The white dashed line represents where a tone was expected. (**a**) Evoked activity is predicted by the presence of tones. The white box highlights an exception, activity where the tone was expected in the case of an early tone. (**b**) The white box indicates a peak in the induced activity where the tone was expected for the case of late tones.*

Induced GBA

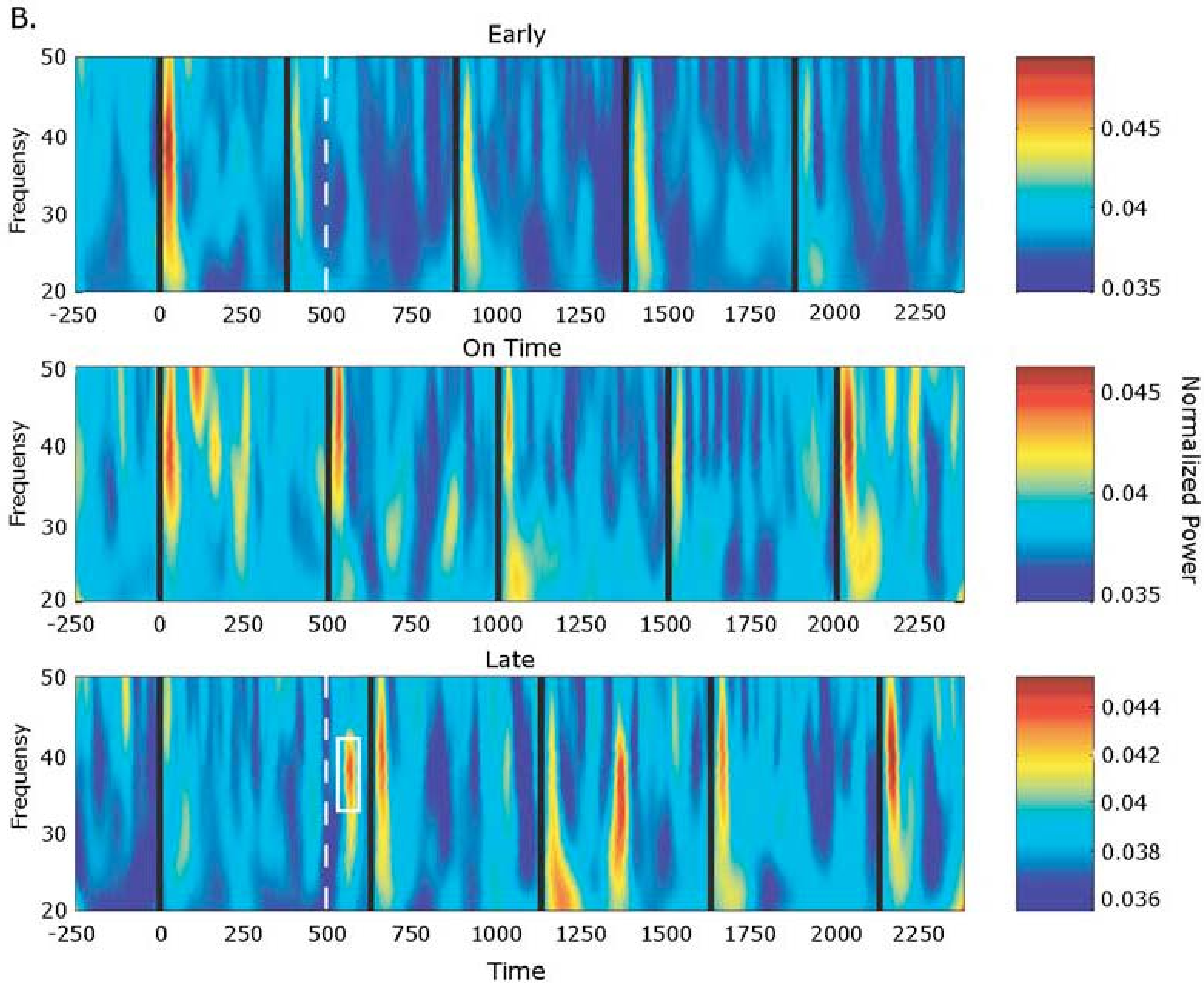


Figure 6.

*Time-frequency representation of the evoked and induced GBA in response to early, late, or on-time tones averaged over all subjects. The white dashed line represents where a tone was expected. (**a**) Evoked activity is predicted by the presence of tones. The white box highlights an exception, activity where the tone was expected in the case of an early tone. (**b**) The white box indicates a peak in the induced activity where the tone was expected for the case of late tones.*

SUMMARY

Evoked GBA appears to represent sensory processing as predicted by the presence of tones, much like the MLR. Induced GBA may reflect temporally precise expectancies for strongly and weakly accented events in sound patterns. Moreover, induced GBA behaves in a manner consistent with perception-action coordination studies using perturbed temporal sequences. Taken together, the characteristics of induced GBA provide evidence for an active, dynamic system capable of making predictions (i.e., anticipation), encoding metrical patterns and recovering from unexpected stimuli.

GBA appears to be a useful neuroelectric correlate of rhythmic expectation and may therefore reflect pulse perception. Due to the anticipatory nature of GBA, it may be supposed there is an attentional dependence. Future research should aim to manipulate attentional state, localize neural sources and further probe the role of induced GBA in meter perception.

Syncopation - violation of metrical expectations

Image removed due to copyright restrictions.
Definition of syncopation with some musical examples.
From Jones, G. T. *Music Theory*. New York, NY: Barnes and Noble Books, 1974.

Rhythmic streaming (segregation/fusion of rhythmic

- African xylophone music
- Timbre effects
- Pitch difference
- Competition of frequency separations

Rhythmic elaboration -subdividing time intervals

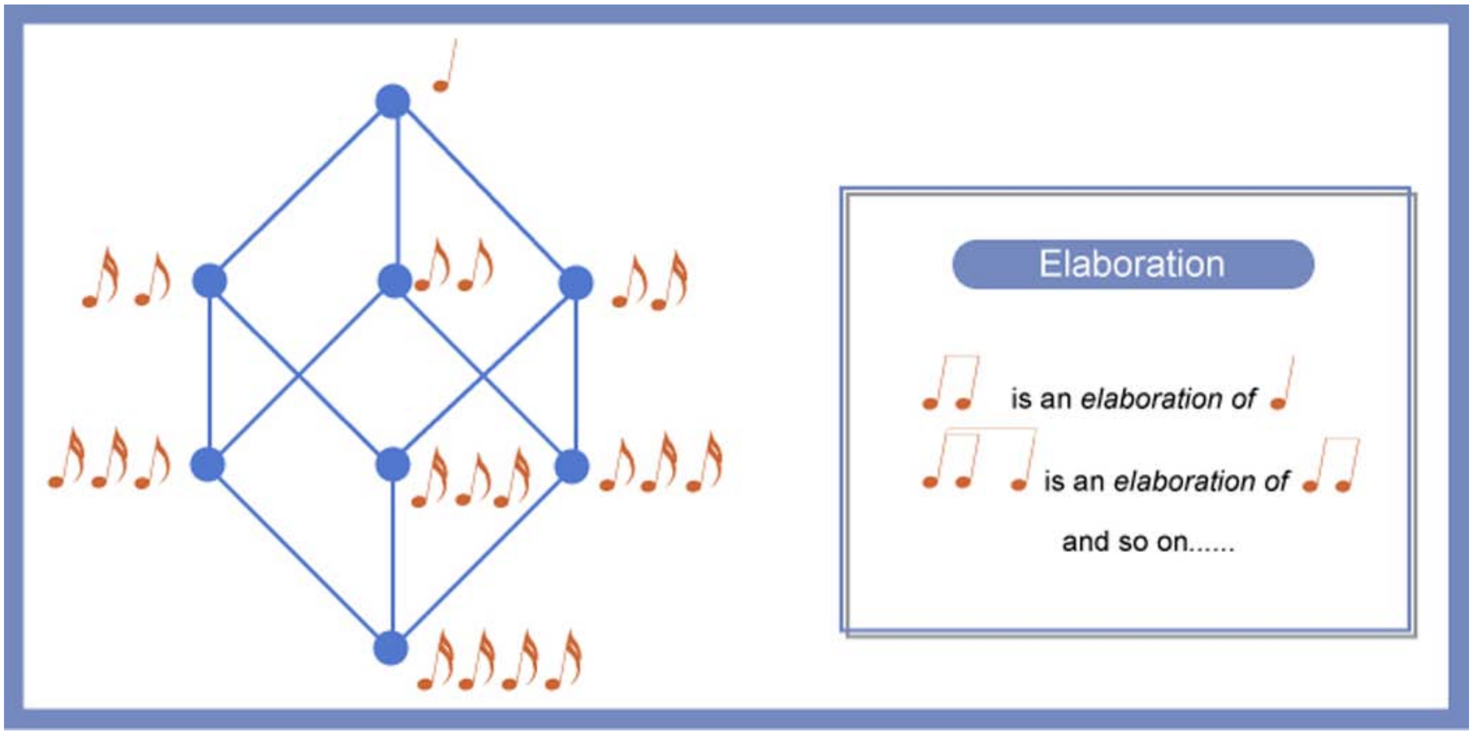
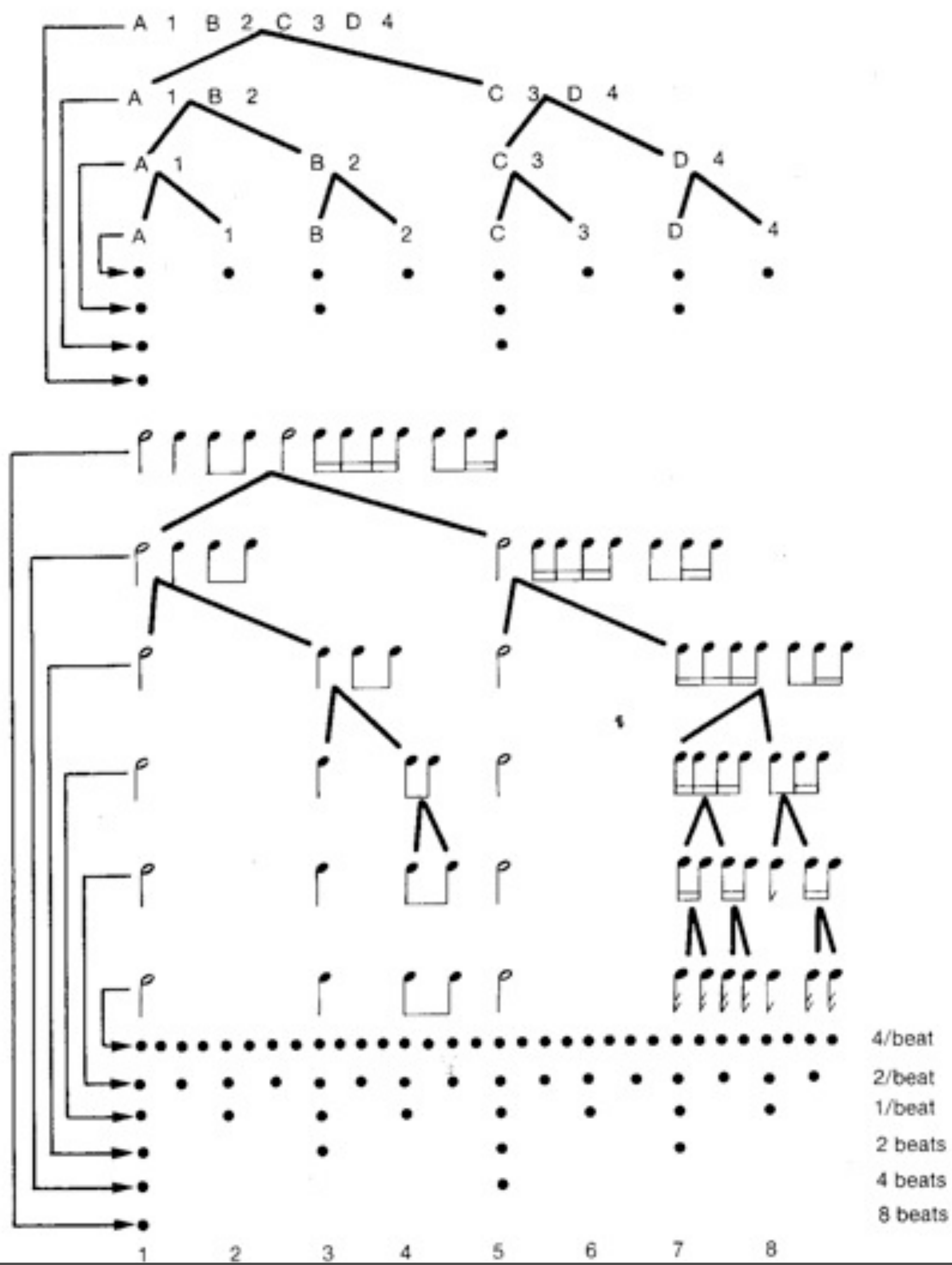


Figure by MIT OpenCourseWare.

Smulevitch & Povel (2000) in Rhythm: Perception & Production, Desain & Windsor eds

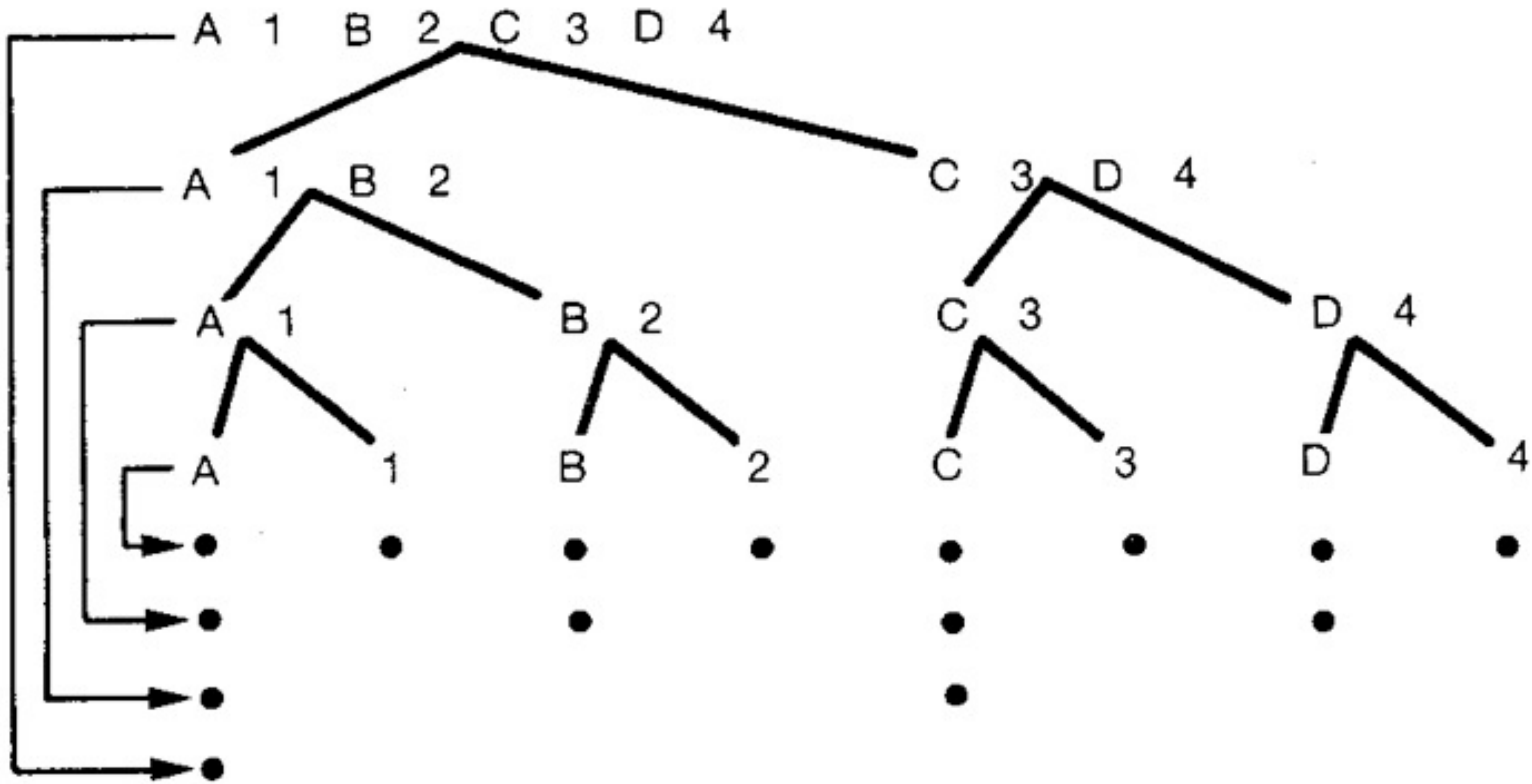
Rhythmic Hierarchy



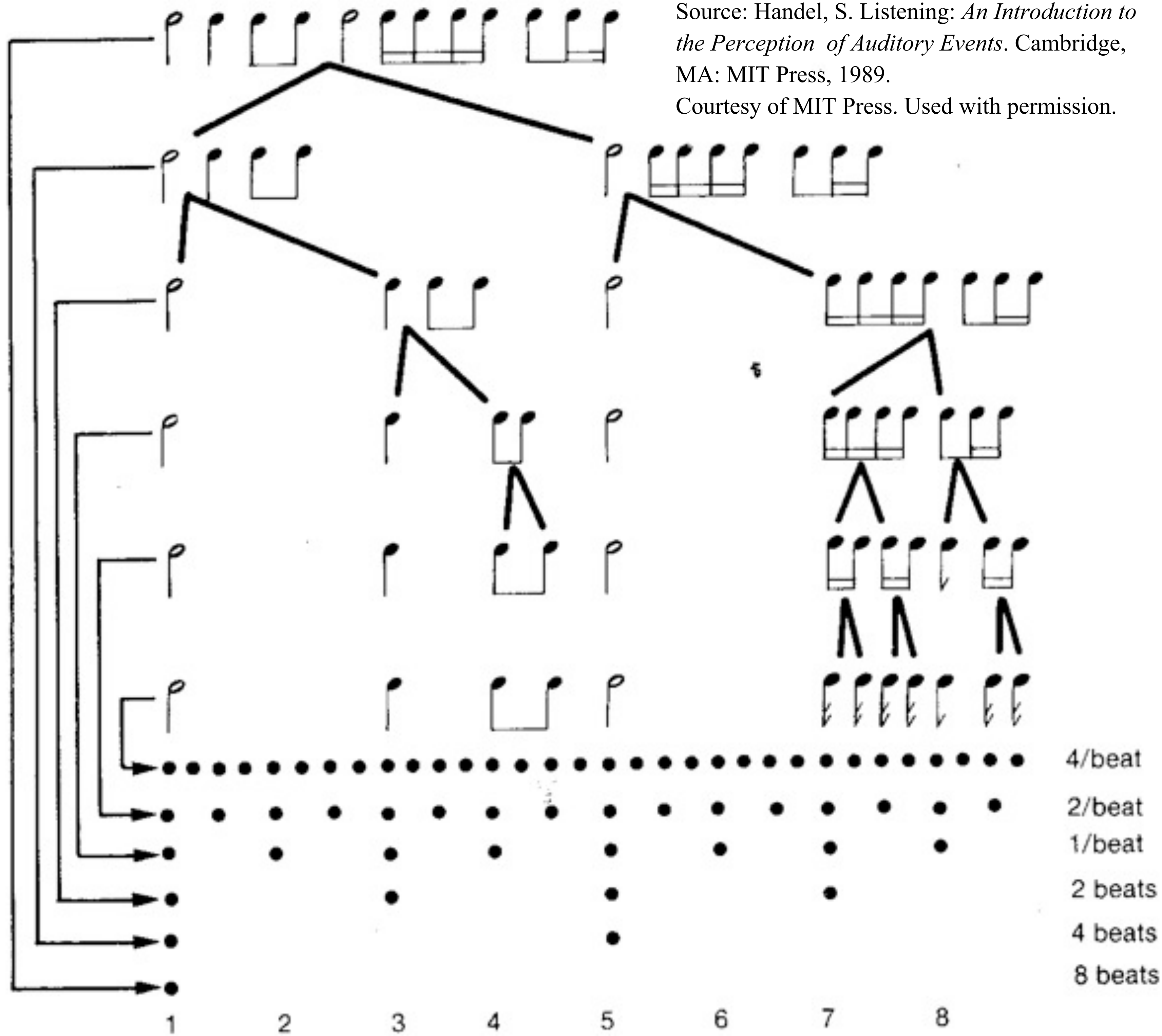
Source: Handel, S. Listening: *An Introduction to the Perception of Auditory Events*. Cambridge, MA: MIT Press, 1989.

Handel

Rhythmic Hierarchy



Handel



Handel

Polyrhythms

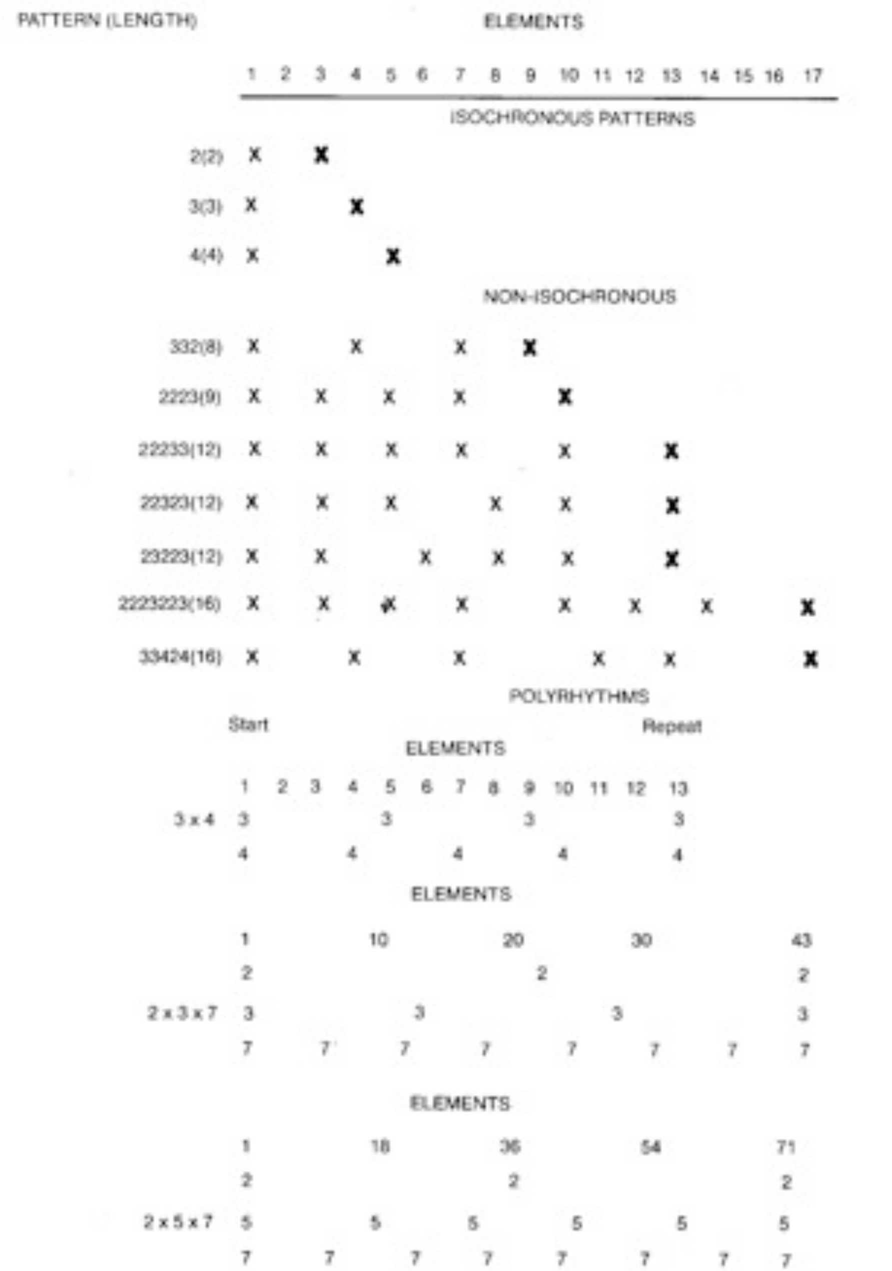


Figure 11.5
Rhythmic patterns that are used in the drum music of Africa. Typically several rhythmic lines are played simultaneously, and often a master drummer improvises on top of the repeating rhythmic patterns. Polyrhythms are defined as the simultaneous presentation of two isochronous patterns that do not share a common denominator. Three examples are shown. The element at which the polyrhythm repeats can be calculated by multiplying the number of elements in each line together (e.g., the pattern 2 × 5 × 7 ends on the 70th element and repeats on the 71st element).

Source: Handel, S. Listening: *An Introduction to the Perception of Auditory Events*. Cambridge, MA: MIT Press, 1989.

Handel

PATTERN (LENGTH)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ISOCHRONOUS PATTERNS																	
2(2)	X		**X**														
3(3)	X			**X**													
4(4)	X				**X**												
NON-ISOCHRONOUS																	
332(8)	X			X			X		**X**								
2223(9)	X		X		X		X			**X**							
22233(12)	X		X		X		X			X			**X**				
22323(12)	X		X		X			X		X			**X**				
23223(12)	X		X			X		X		X			**X**				
2223223(16)	X		X		X		X			X		X		X			**X**
33424(16)	X			X			X				X		X				**X**

ELEMENTS

Source: Handel, S. Listening: *An Introduction to the Perception of Auditory Events*. Cambridge, MA: MIT Press, 1989.

Polyrhythms (polyrhythms:rhythm::polyphony:melody)

Source: Handel, S. Listening: *An Introduction to the Perception of Auditory Events*. Cambridge, MA: MIT Press, 1989.

Conlon Nancarrow

POLYRHYTHMS

Start — Repeat

ELEMENTS

	1	2	3	4	5	6	7	8	9	10	11	12	13
3 x 4	3				3				3				3
	4			4			4			4			4

ELEMENTS

1 10 20 30 43

2 2 2

2 x 3 x 7 — 3 3 3 3

7 7 7 7 7 7 7 7

ELEMENTS

1 18 36 54 71

2 2 2

2 x 5 x 7 — 5 5 5 5 5 5

7 7 7 7 7 7 7 7

Handel

Rhythm & Grouping

- Three examples from
- Bregman & Ahad
- Auditory Scene Analysis CD
- African xylophone music

interference between rhythmic patterns

separation of patterns via pitch differences

separation of patterns via timbral diffs

Conflicting rhythms interfere unless the events can be separated out in separate streams

Metrical vs. rhythmic phrases (rel. independence)

(Snyder, Music & Memory)

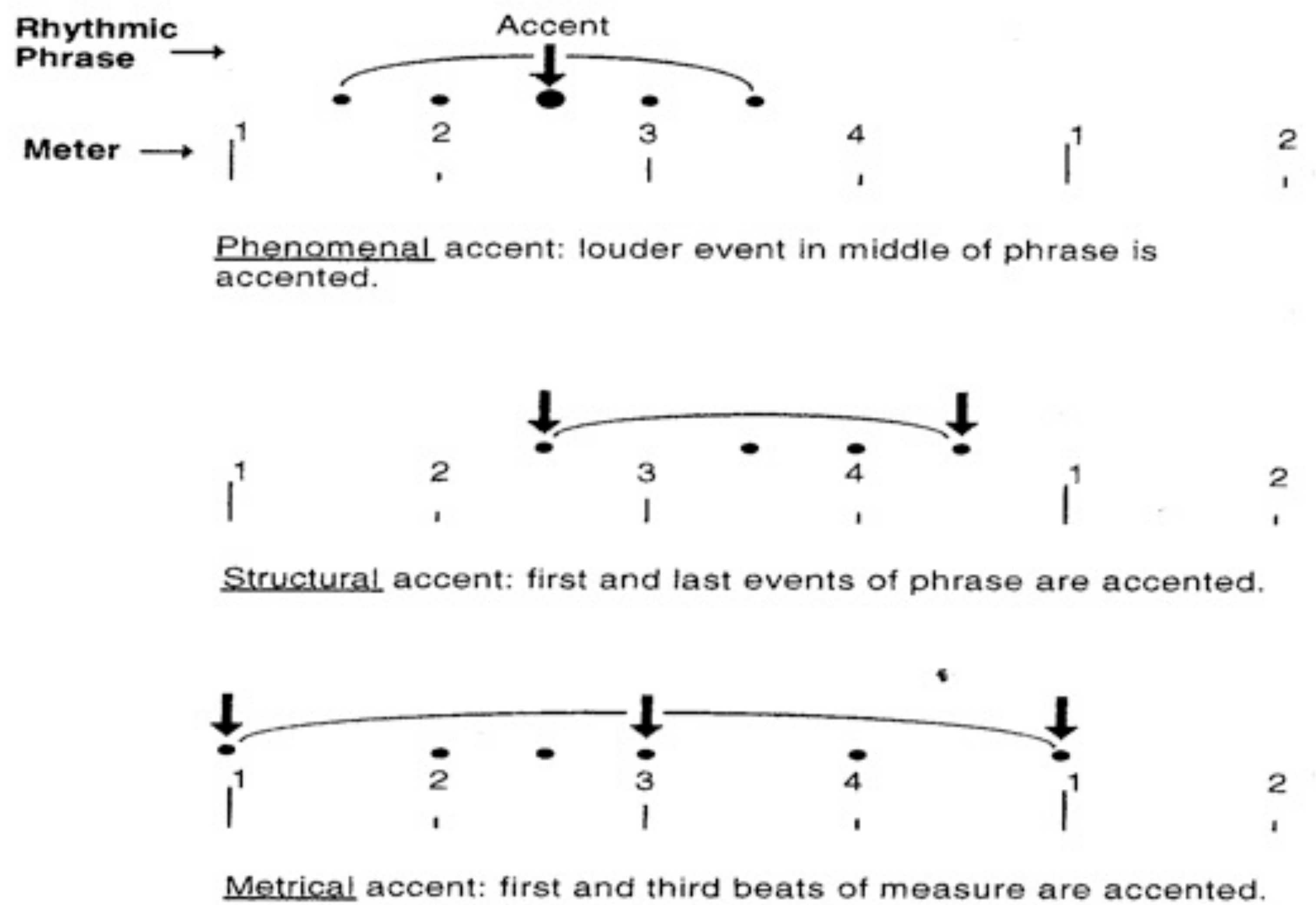


Figure 12.4
Three kinds of accent.

Source: Snyder, Bob. *Music and Memory.* Cambridge, MA: MIT Press, 2000. Courtesy of MIT Press. Used with permission.

Major points -- rhythm

Rhythm involves perception of temporal patterns of events

Recurring patterns group into chunks that create expectations of future temporal occurences of events **(rhythmic pattern induction)**

Rhythmic grouping occurs on the same timescale as melodic grouping.

We also infer a metrical grid that involves a regular set of timepoints (pulse, tatum) and a regular pattern of accented/ unaccented events (meter). **(Metrical induction)**

Expectations generated from rhythmic grouping and metrical induction processes can be manipulated for tension-relaxation effect.

Time, memory, and anticipation

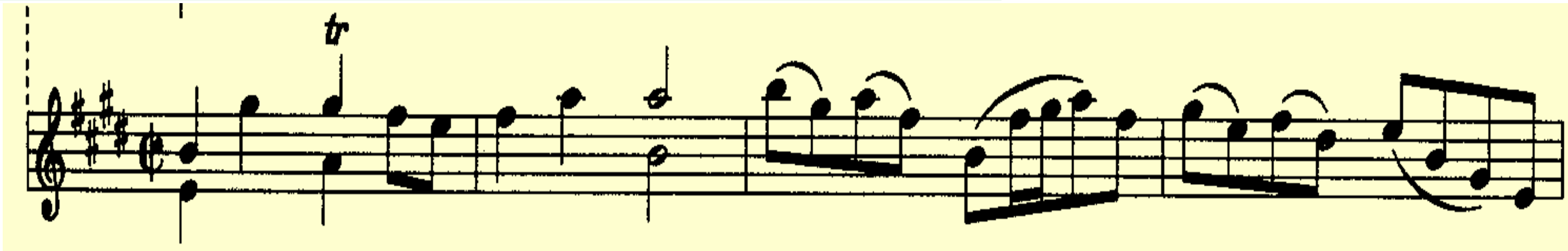


Image of Salvador Dali's painting "The Persistence of Memory"
removed due to copyright restrictions.
See http://en.wikipedia.org/wiki/File:The_Persistence_of_Memory.jpg

Temporal integration windows

(Snyder, Music & Memory)

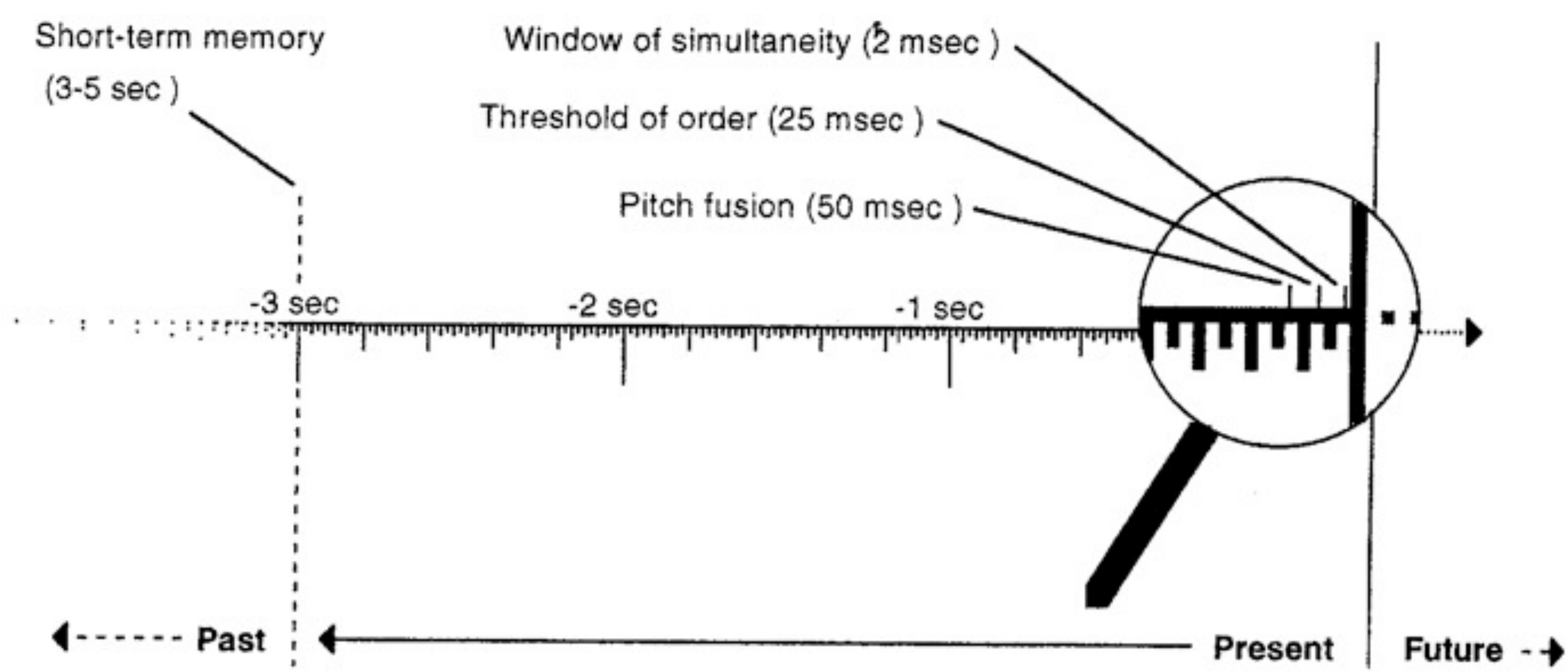


Figure 2.2
Brain processes and musical time.

Timescales & memory

(Snyder, Music & Memory)

Table 1.1
Three Levels of Musical Experience

	Events per second	Seconds per event
	16,384	1/16,384
EVENT FUSION	8,192	1/8,192
(early processing)	4,096	1/4,096
	2,048	1/2,048
Functional units =	1,024	1/1,024
individual *events* and	512	1/512
boundaries; pitches,	256	1/256
simultaneous intervals,	128	1/128
loudness changes, etc.	64	1/64
	32	1/32
MELODIC and RHYTHMIC	16	1/16
GROUPING	8	1/8
(short-term memory)	4	1/4
Functional units =	2	1/2
patterns; rhythmic and	1	1
melodic groupings,	1/2	2
phrases.	1/4	4
	1/8	8
	1/16	16
FORM	1/32	32
(long-term memory)	1/64	1 min 4 sec
Functional units =	1/128	2 min 8 sec
large scale *constancies*;	1/256	4 min 16 sec
sections, movements,	1/512	8 min 32 sec
entire pieces.	1/1,024	17 min 4 sec
	1/2,048	34 min 8 sec
	1/4,096	1 hr 8 min 16 sec.

melodic and rhythmic grouping," and the "level of musical form" (see table 1.1).[16] The three types of processing define three basic time scales on which musical events and patterns take place.

Memory & grouping

(Snyder, Music & Memory)

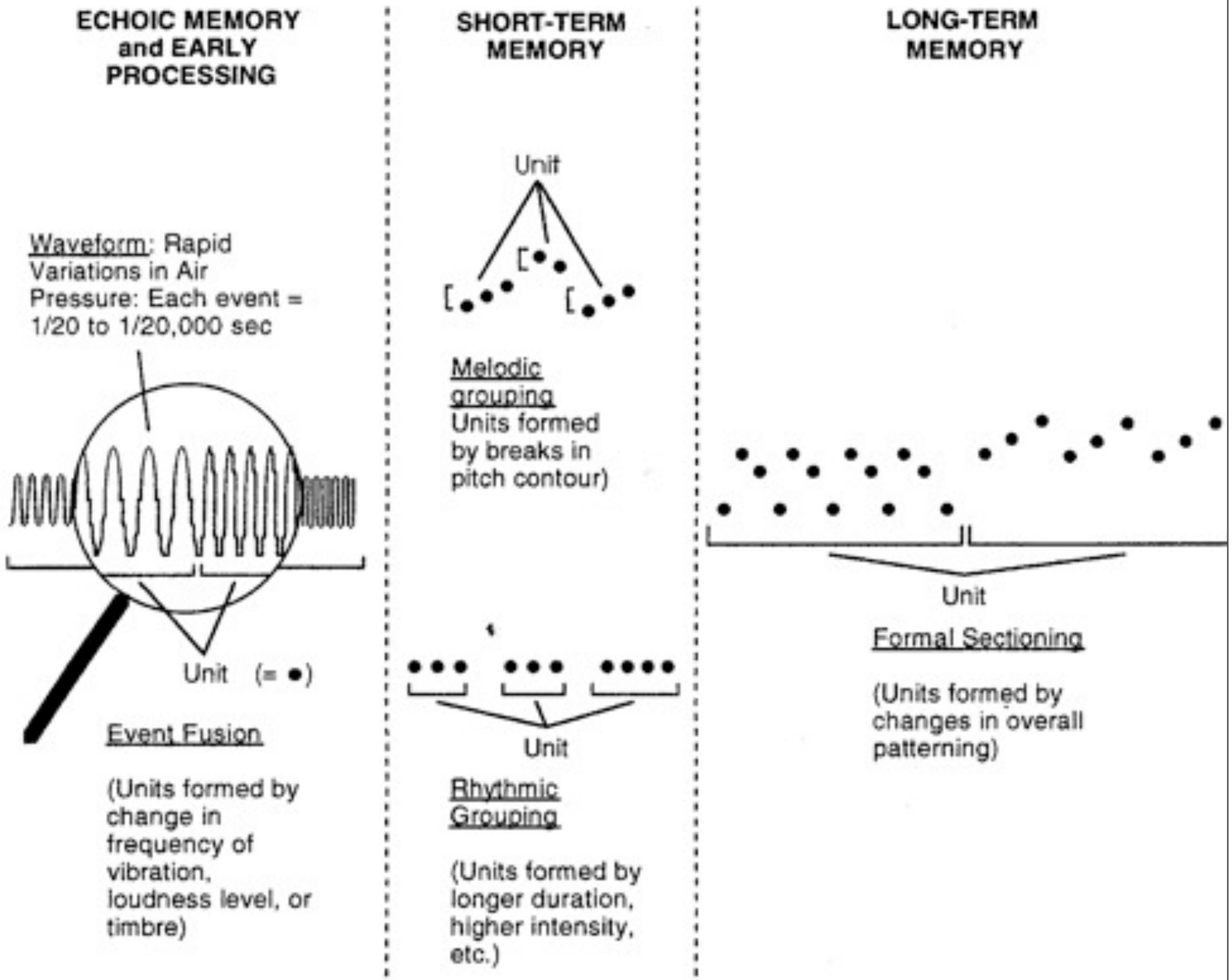


Figure 3.1
Levels of sequential grouping: Event fusion, melodic and rhythmic grouping, and formal sectioning. Note that pattern formation at each level requires comparison of events over increasing time spans. Event fusion requires comparison within 250 msec, melodic and rhythmic patterns require comparison across a time span of from 250 msec to 8 sec, and formal sections require comparisons across a time span of from 8 sec to as much as 1 hour. Also note that each individual unit at one level becomes a part of a unit at the next level up.

Memory processes generate musical context

Tonality induction -- repetition of particular notes & sets of harmonics that establishes a tonal expectation through which all subsequent incoming tonal patterns are processed -- establishment of the tonic

Rhythmic induction -- repetition of patterns of accented and unaccented events that establishes a temporal pattern of expectation for subsequent events

Both kinds of induction operate on similarities and contrasts between previous and subsequent sounds & events

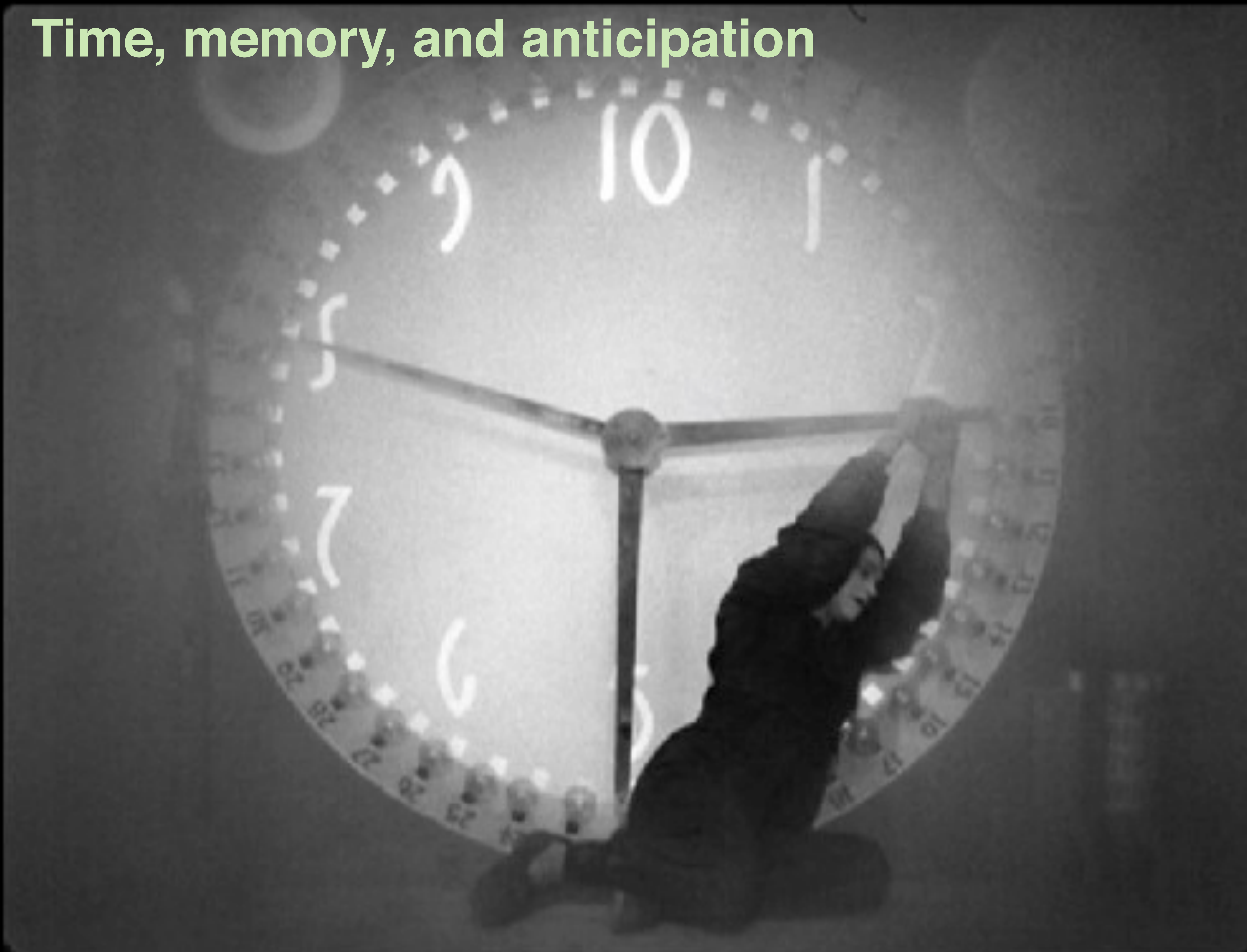
OLD + NEW heuristic:

1) OLD incoming patterns similar to previous ones build up the images of previous ones, confirm + strengthen expectations, create relaxation

2) NEW different patterns create contrasts that violate expectations established from previous inputs, create tension

3) degree of contrast (distance in perceptual space) determines

Time, memory, and anticipation



Time

- What is time? Newtonian & Bergsonian time
- The perception of time
  - Duration, succession, and perspective
  - Relativity of time
  - Constant Weber fraction for time estimation
  - Aging & time perception (internal clocks slow down)
  - Duration and event-density
- Learning & temporal prediction (anticipation)
- Brains as temporal prediction machines
- Models of time (interval) perception & production
  - Clock models -- accumulators (hourglass)
  - Oscillator models (pendulum)
  - Delay-detectors and static representations of time
  - Rhythmic hierarchies, simple ratios, and groupings
  - Temporal memory traces (delay loops, cyclochronism)

Time

"time…does not exist without changes." Aristotle, Physics, IV

Time as an absolute world-coordinate (Newtonian time) vs. time as epistemic change (psychological, Bergsonian time)

"A man in sound sleep, or strongly occupy'd with one thought, is insensible of time… Whenever we have no successive peceptions, we have no notion of time, even tho' there be a real succession in the objects…time cannot make its appearance to the mind, either alone, or attended with a steady unchangeable object, but is always discovered by some perceivable succession of changeable objects." Hume as quoted in Fraisse, pp. 3-4

Measurement of time

How is time measured, psychologically, by the neural mechanisms and informational organizations that constitute our minds?

Duration

60 BPM

152 BPM

Our sense of the length of time (Fraisse, 1962, The Psychology of Time)

Constant Weber fractions for interval estimation

- Errors are proportional to the interval estimated
- Weber's law for timing; jnd's on the order of 8-12%
- depending on modality (hearing, touch, vision)

Temporal prediction of reward in conditioning

- (Scalar timing intimately related to the response latency in conditioning when interval between stimulus and reward are varied, see R. Church, A Concise Introduction to Scalar Timing Theory, 2003. See also Fraisse's (1963) discussion of Pavlov and Popov cyclochronism model)

Some general observations (Fraisse via Snyder, Music & Memory):

Filled time durations appear shorter than empty ones

Rate of novel events makes durations appear shorter

- (monotonous durations are experienced as longer, but remembered as shorter)

Aging: young children overestimate durations; older adults underestimate durations

- (A systematic change in internal timing mechanisms with age? cf Δabsolute pitch)

Implications for music: pieces with high event densities go faster; those with low ones seem to take forever; duration is in the mind of the beholder and his/her expectations

Beat induction and duration discrimination

Weber's Law

Image removed due to copyright restrictions.
Graph illustrating Weber's Law. See Fig. 4.13 in Jones and Yee, "Attending to auditory events: the role of temporal organization." In *Thinking in Sound*. Edited by E. Bigand and S. McAdams. New York, NY: Oxford University Press, 1993. ISBN: 9780198522577.

Succession

Time order:

before and after (Fraisse, Snyder)

Our recollection of time order depends on memory mechanisms, how distant in the past were the events

Representation of order in long-term memory is poor

LTM is massively parallel, not serial

Time order within chunks is better preserved than between them

Primacy and recency: first and last elements in a chunk best remembered, most salient

Perspective: Past, present, future

Mediated by different psych/brain mechanisms

Past: long term memory

Present: working memory

Future: anticipation, planning

Music (like sports) focuses our minds on the present, on events that have occurred in the last few seconds to minutes.

Mechanisms of timing and temporal processing

- Temporal contiguity models of learning
- Clock models
  - Switched accumulator, e.g. hourglass
  - Explicit measurement of time durations
  - Ordering of durations by magnitude
- Time delay detectors/generators
  - Array of tuned delay elements, detectors, oscillators
  - Explicit measurement of time durations; storage of patterns
  - Generators of time delays (timers)
- Rhythmic hierarchies (Jones)
  - well-formed patterns create strong expectations
- Temporal memory trace
  - Timeline of events stored in reverberating memory
  - Readout of events & (timing of) their consequences

Temporal expectations on different timescales

- Pitch: repetitions on microtemporal timescales (200 usec to 30 ms)
- Infra-pitch: not well defined, repetitions with periods 30-100 ms
- Rhythms: patterns of individuated events with periods 100 ms to several secs
- Longer temporal expectations (> few secs)

Metrical and nonmetrical patterns (cf. tonal & atonal melodies)

Jones & Yee,
Attending to auditory events:
the role of temporal organization
in Thinking in Sound

Temporal reproductions are better for well-formed temporal patterns

See Fig. 4.9 in Jones and Yee, "Attending to auditory events: the role of temporal organization." In *Thinking in Sound*. Edited by E. Bigand and S. McAdams. New York, NY: Oxford University Press, 1993. ISBN: 9780198522577.

Higher-order (longer-range) metrical patterns

Image removed due to copyright restrictions.
See Fig. 4.7 in Jones and Yee, "Attending to auditory events: the role of temporal organization." In *Thinking in Sound*. Edited by E. Bigand and S. McAdams. New York, NY: Oxford University Press, 1993. ISBN: 9780198522577.

Hierarchical & nonhierarchical ratios of event timings

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See Fig. 4.10 in Jones and Yee, "Attending to auditory events: the role of temporal organization." In *Thinking in Sound*. Edited by E. Bigand and S. McAdams. New York, NY: Oxford University Press, 1993. ISBN: 9780198522577.

Clock & hierarchical models of beat perception

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See Fig. 4.11 in Jones and Yee, "Attending to auditory events: the role of temporal organization." In *Thinking in Sound*. Edited by E. Bigand and S. McAdams. New York, NY: Oxford University Press, 1993. ISBN: 9780198522577.

Mechanisms of timing and temporal processing

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  - Array of tuned delay elements, detectors, oscillators
  - Explicit measurement of time durations; storage of patterns
  - Generators of time delays (timers)
- Rhythmic hierarchies (Jones)
  - well-formed patterns create strong expectations
- Temporal memory trace
  - Timeline of events stored in reverberating memory
  - Cylcochronism (Popov, see Fraisse, memory store is itself temporal)
  - Readout of events & (timing of) their consequences

Warren: Holistic & analytic sequence recognition

holistic: temporal compounds (cohere into unified patterns)

analytic: explicit ID of elements and orders

Timescale similarities & differences of temporal processing

- On all timescales:
  - mechanisms for internalizing timecourses of events, for building up temporal patterns
- Differences between timescales
  - Pitch: support of multiple patterns (pitch mechanism low harmonics) => temporal "transparency", non-interference
  - Rhythm: interference between patterns unless separated into different streams
  - another way of thinking about this is that for rhythm stream formation mechanism is not based on periodicity alone

Time-delay nets

Licklider's (1951) duplex model of pitch perception

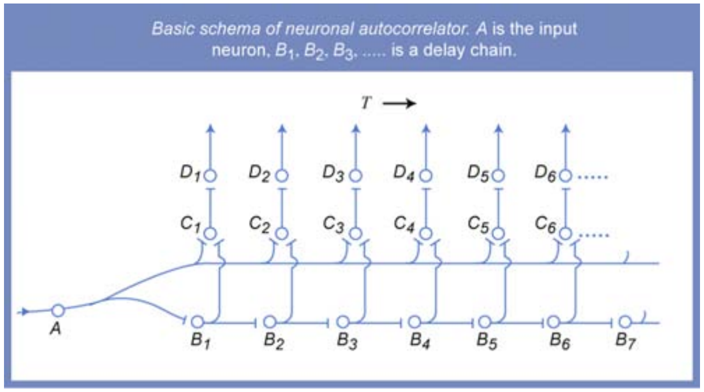


Figure by MIT OpenCourseWare.

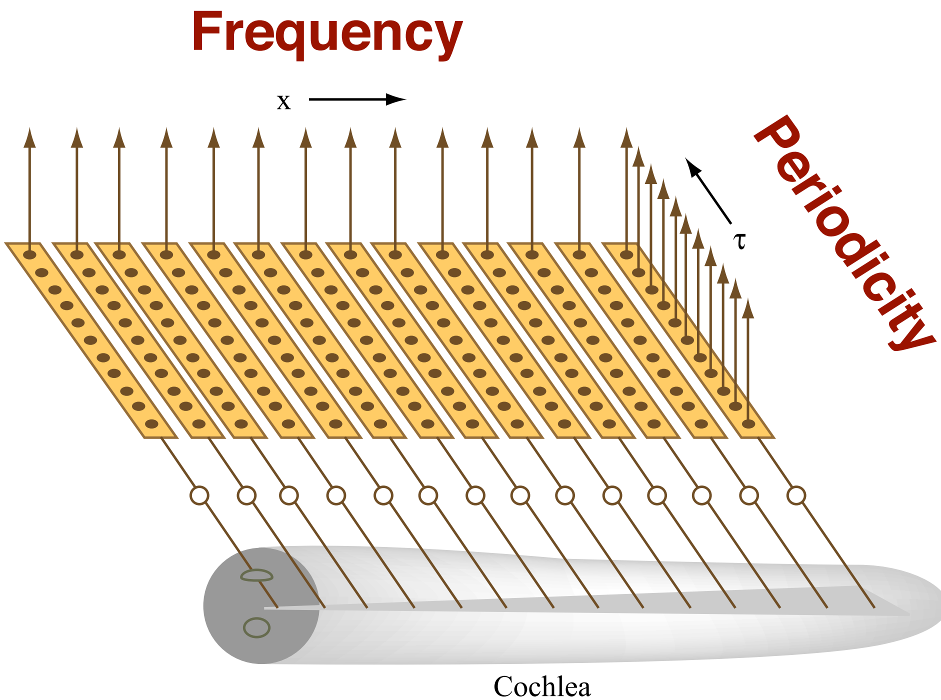


Figure by MIT OpenCourseWare.

Licklider's binaural triplex model

Image removed due to copyright restrictions.

J.C.R. Licklider (1959) "Three AuditoryTheories" in Psychology: A Study of a Science, Vol. 1, S. Koch, ed., McGraw-Hill, pp. 41-144.

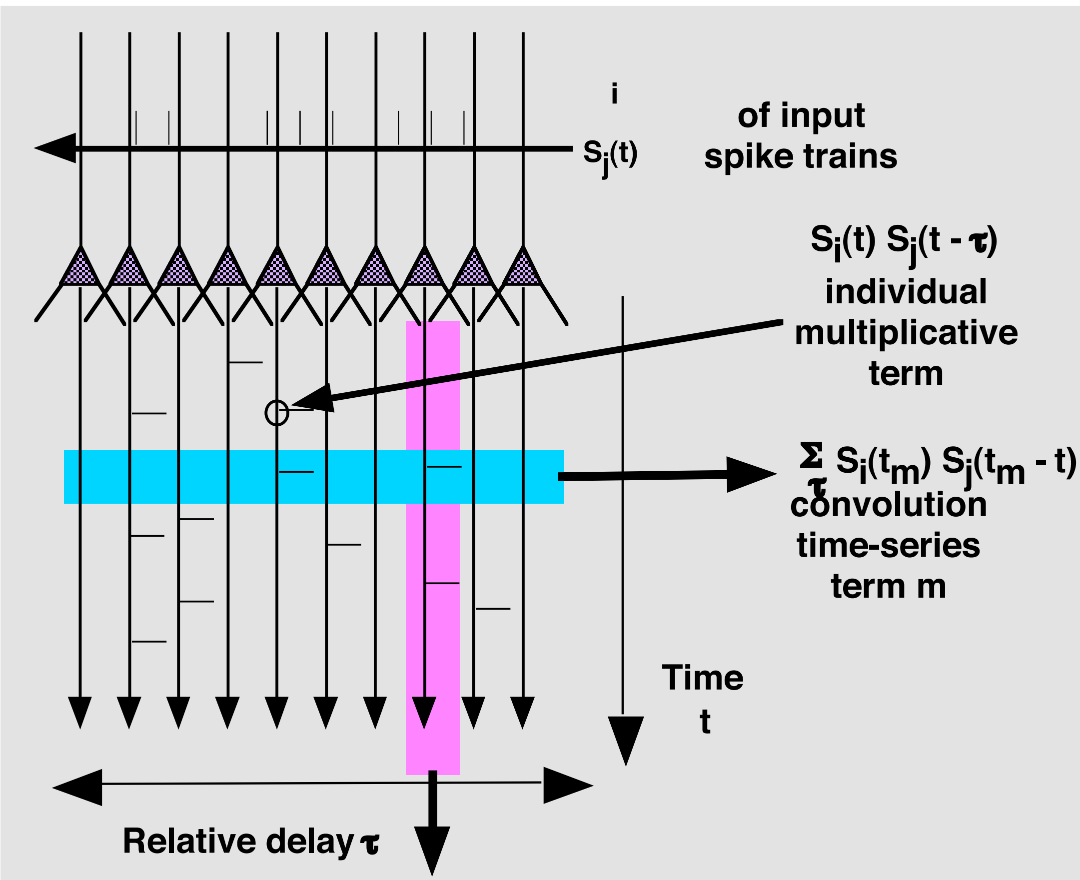
Neural timing nets

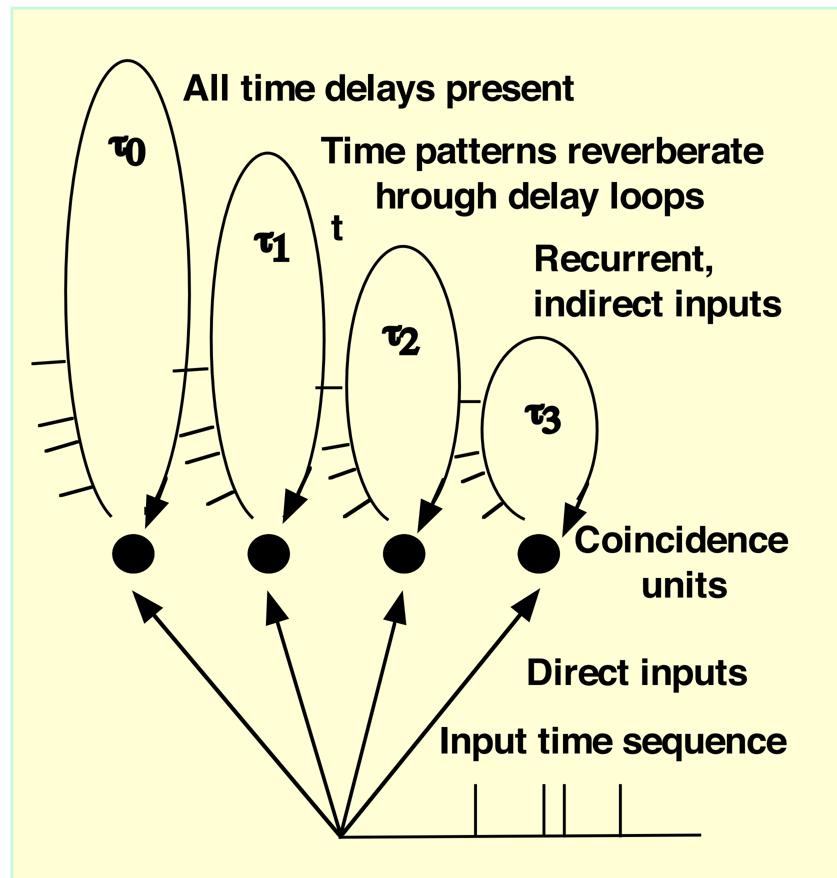
FEED-FORWARD TIMING NETS

- Temporal sieves
- Extract (embedded) similarities
- Multiply autocorrelations

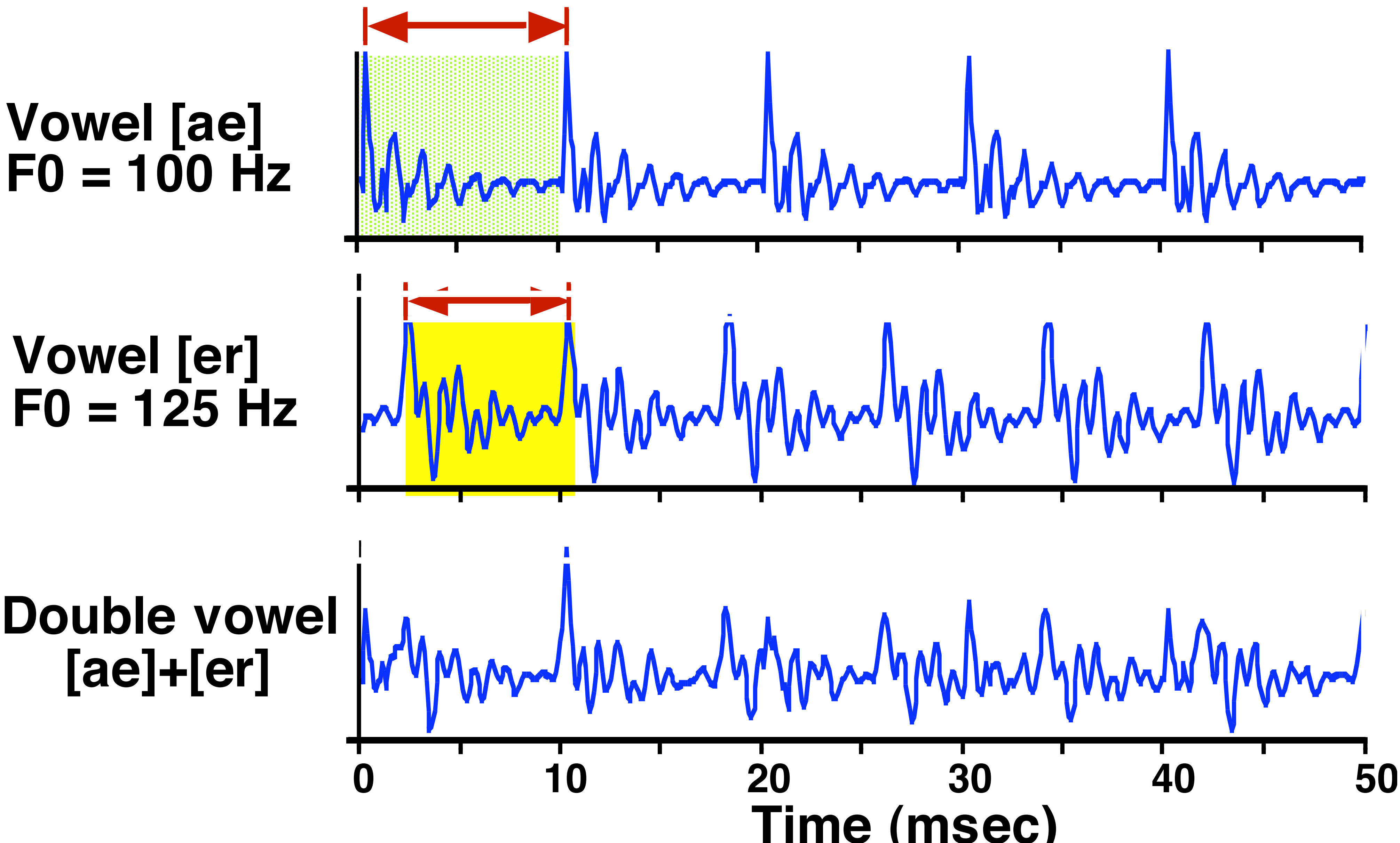
RECURRENT TIMING NETS

- Build up pattern invariances
- Detect periodic patterns
- Separate auditory objects

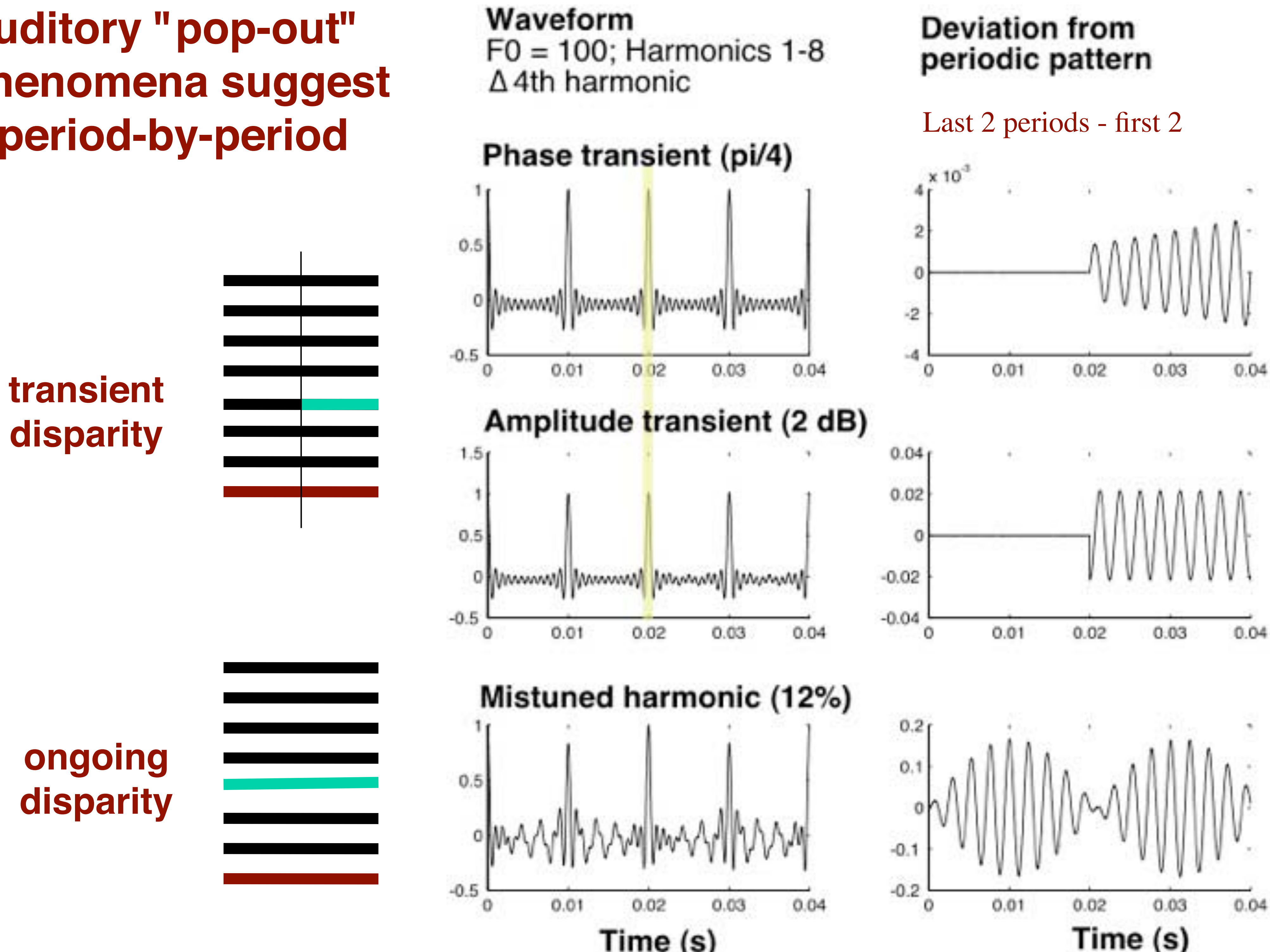




Is a time-domain strategy possible?
Effect of different F0s in the time domain



Auditory "pop-out" phenomena suggest a period-by-period



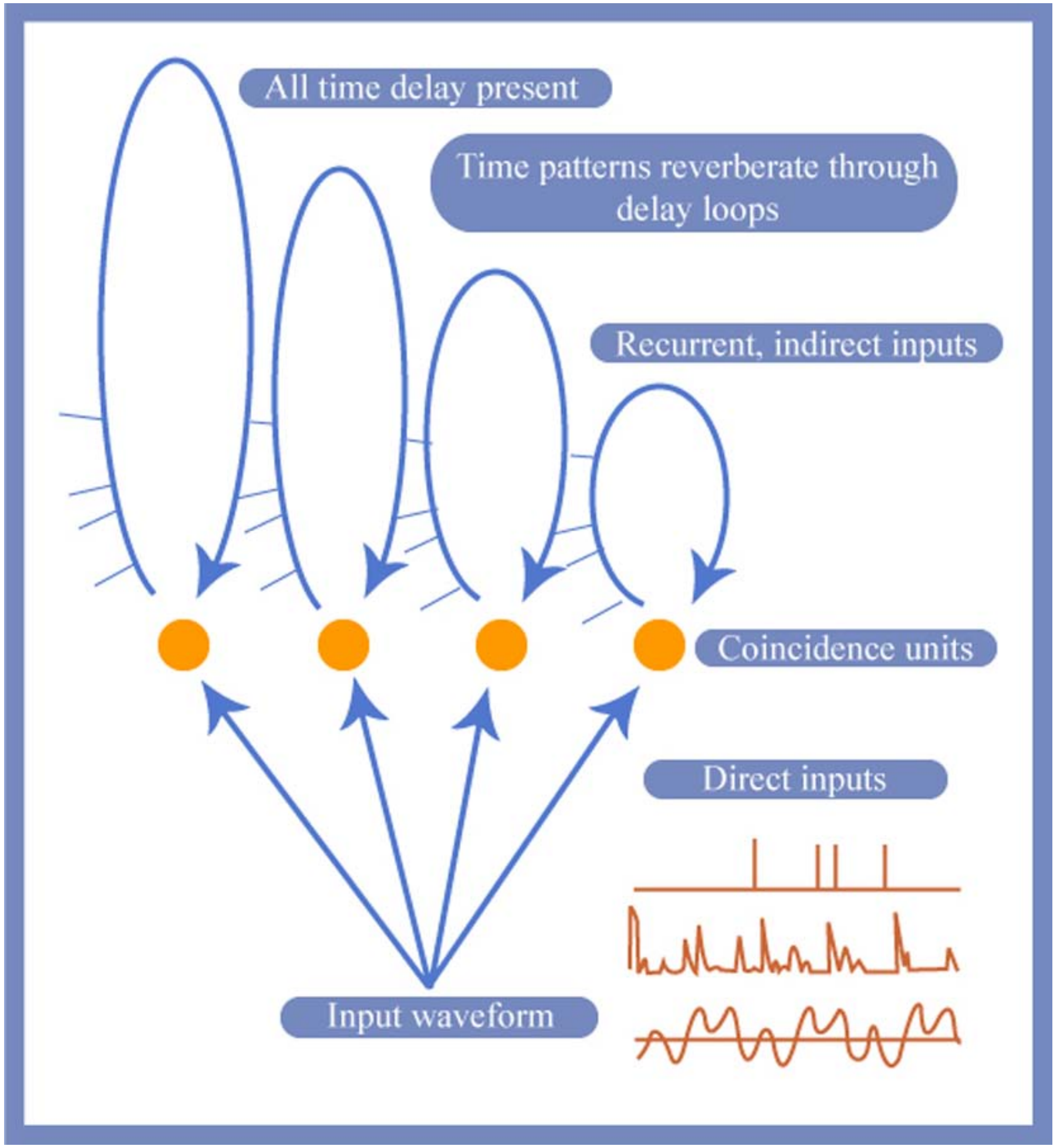
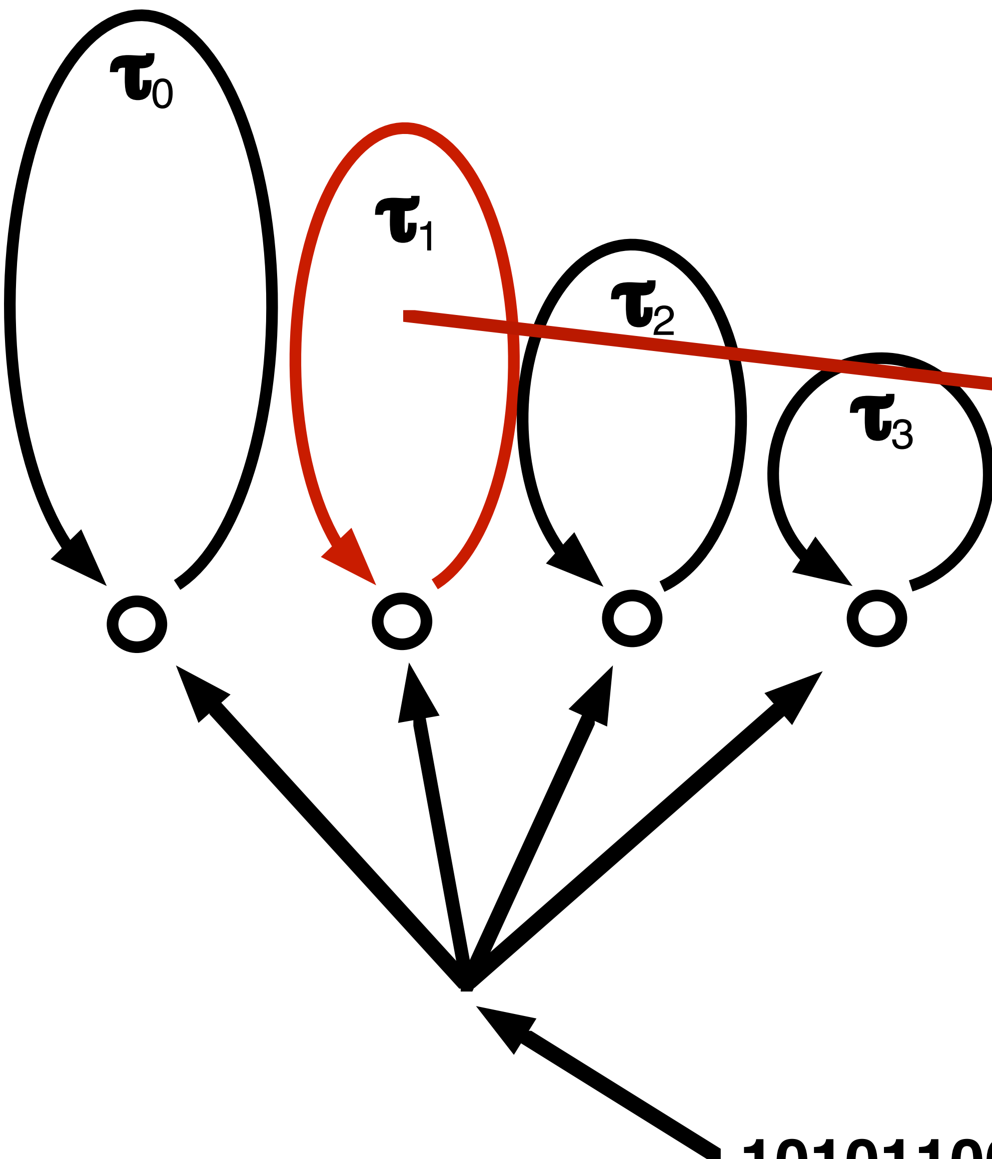
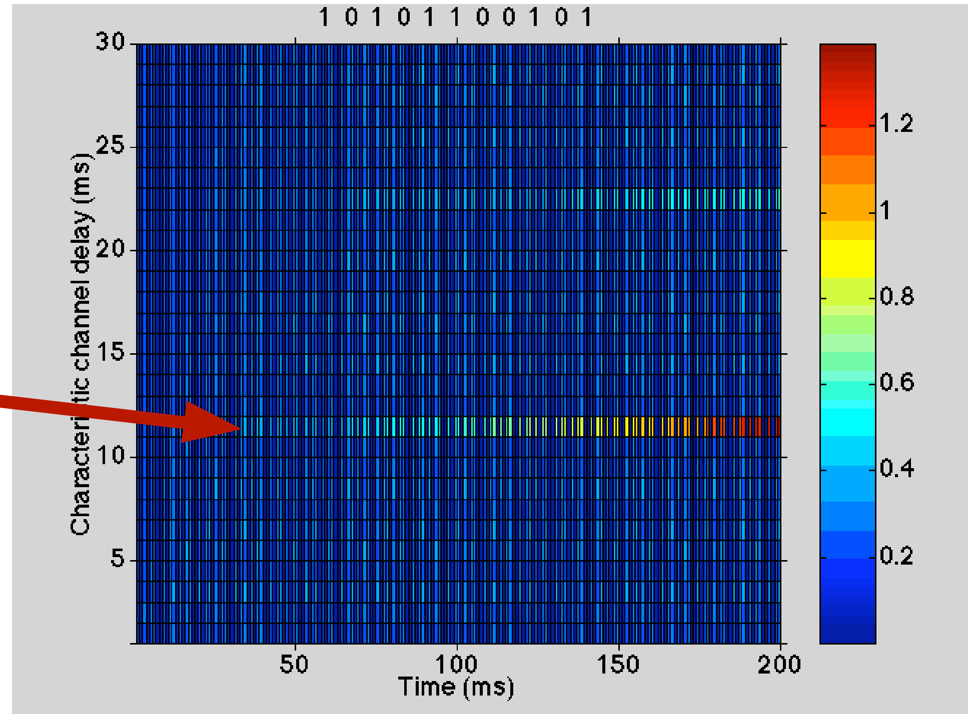


Figure by MIT OpenCourseWare.

Detection of arbitrary periodic patterns

Periodic patterns invariably build up in delay loops whose recurrence times equals the period of the pattern and its multiples.

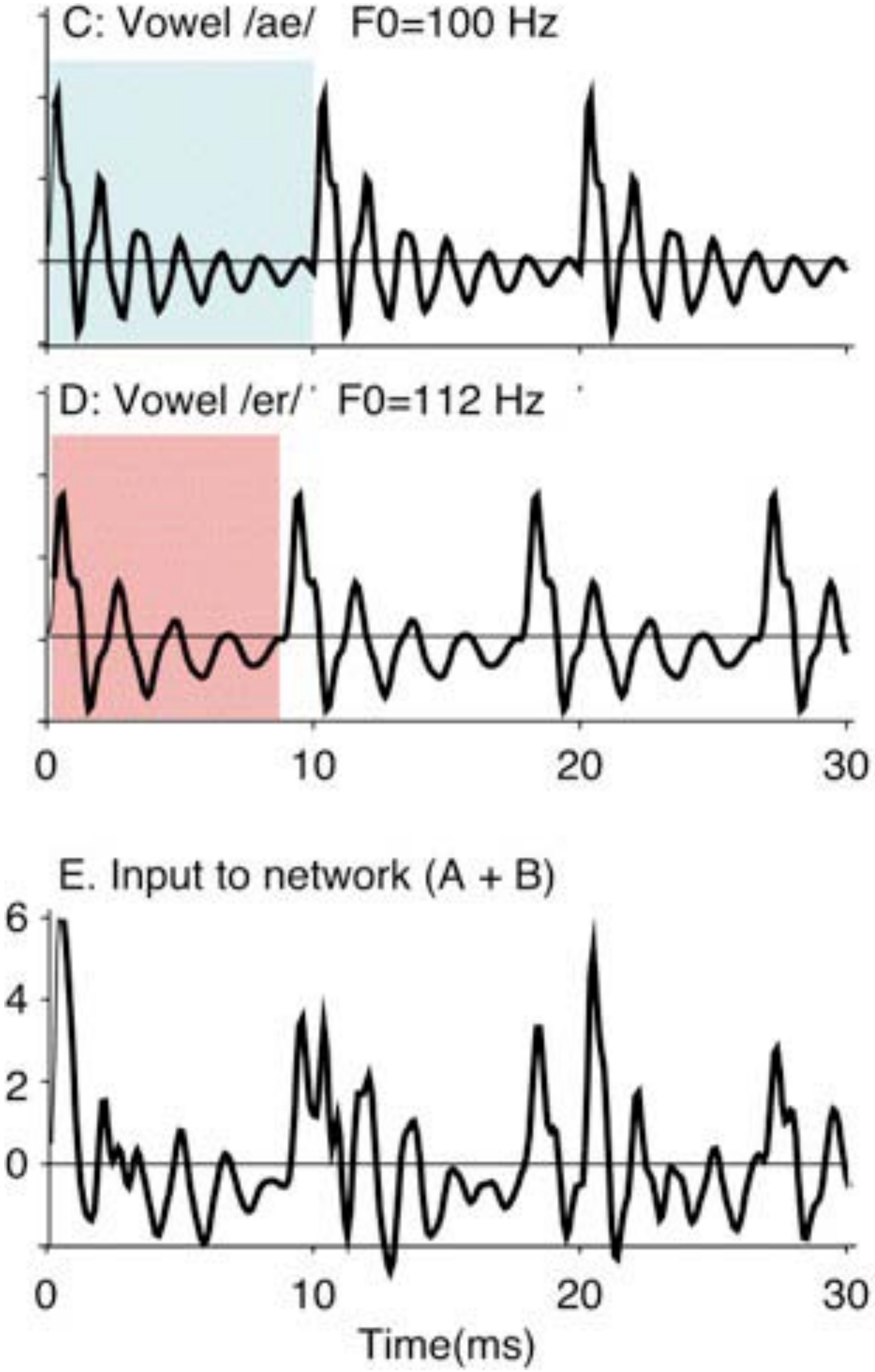




τ_1 = 11 ms = recurrence time of input pattern10101100101

Input pattern

10101100101**10101100101****101011001011010...**



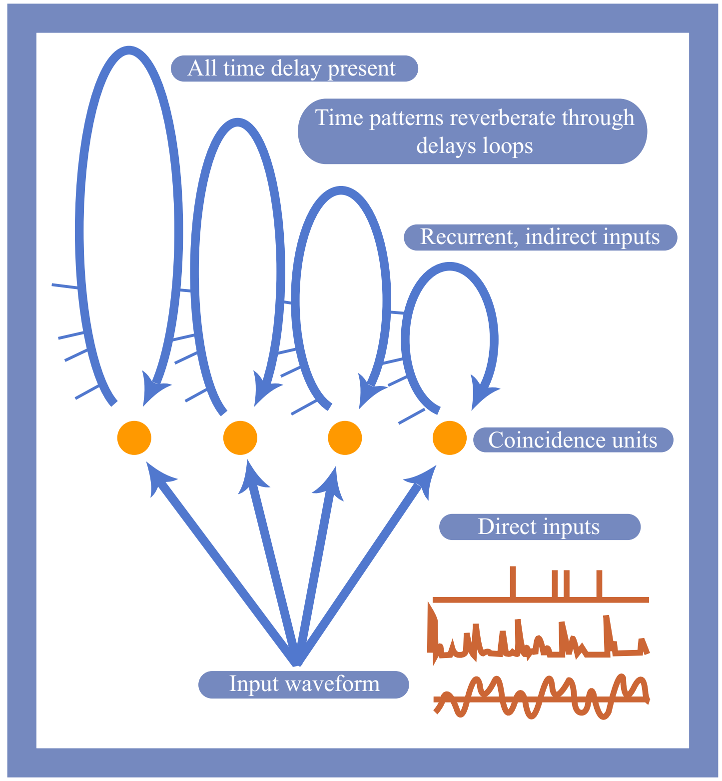
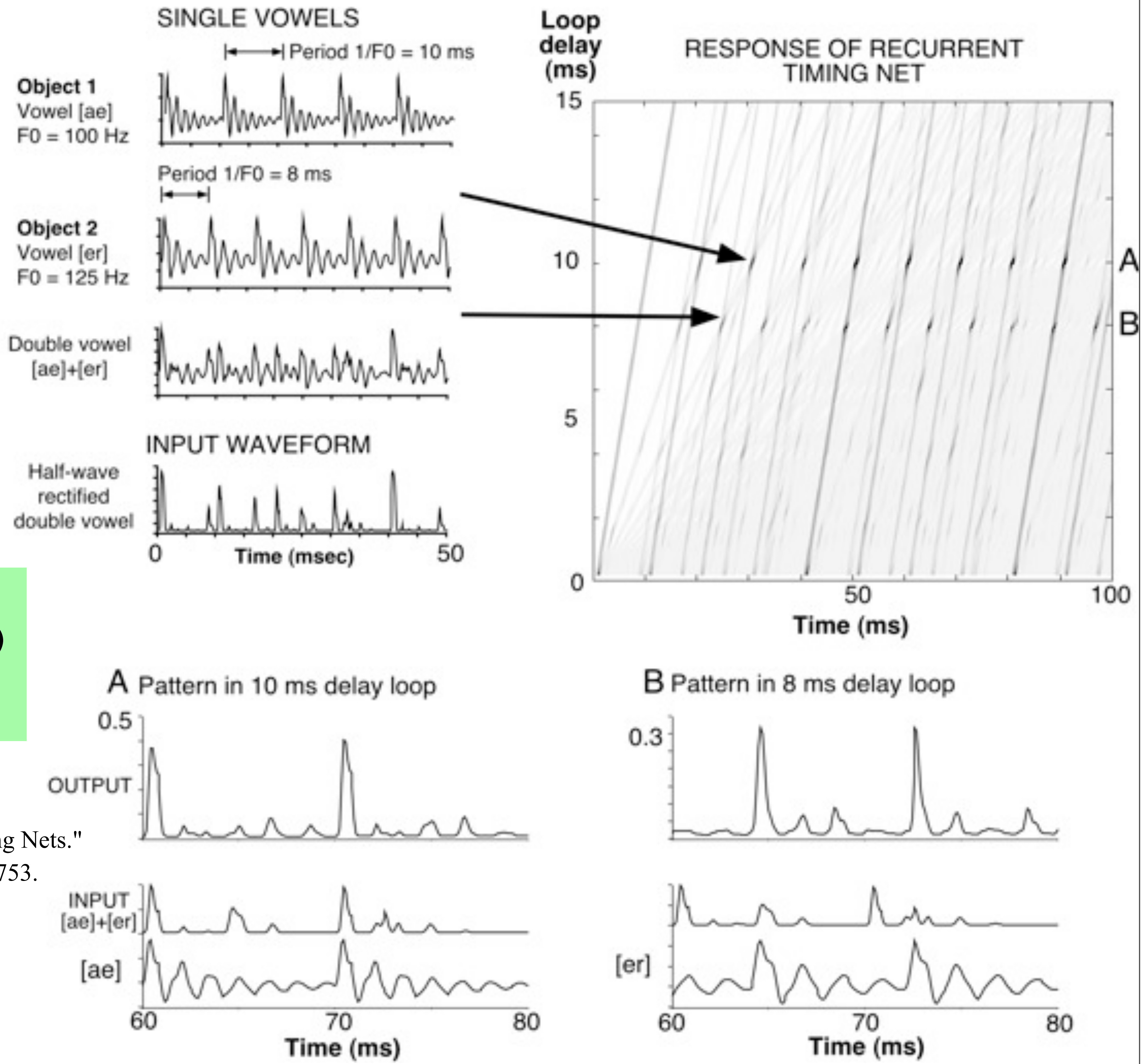


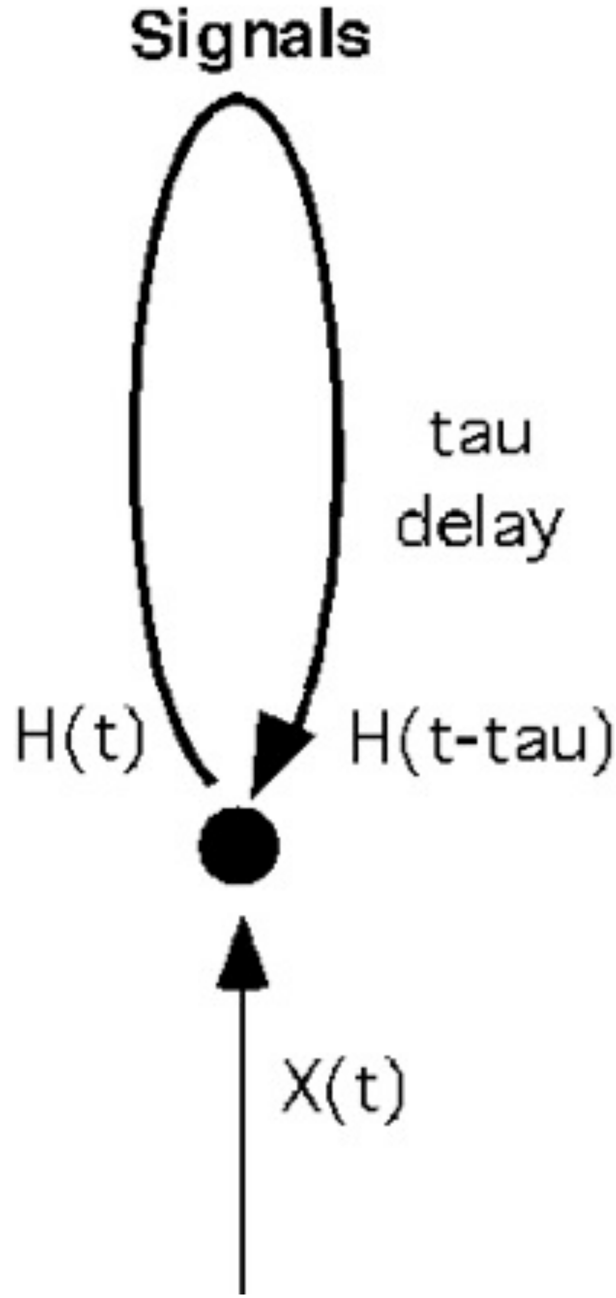
Figure by MIT OpenCourseWare.

Recurrent timing net with single



Revised buildup rule: Min(direct, circulating) plus a fraction of their absolute difference

Source: Cariani, P. "Neural Timing Nets." *Neural Networks* 14 (2001): 737-753. Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

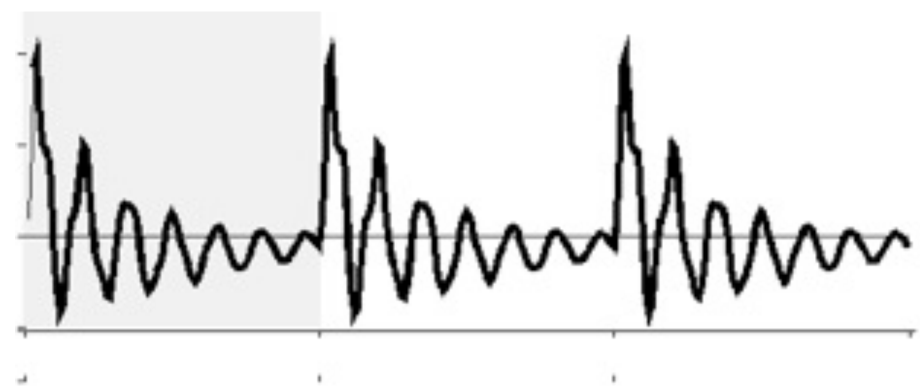


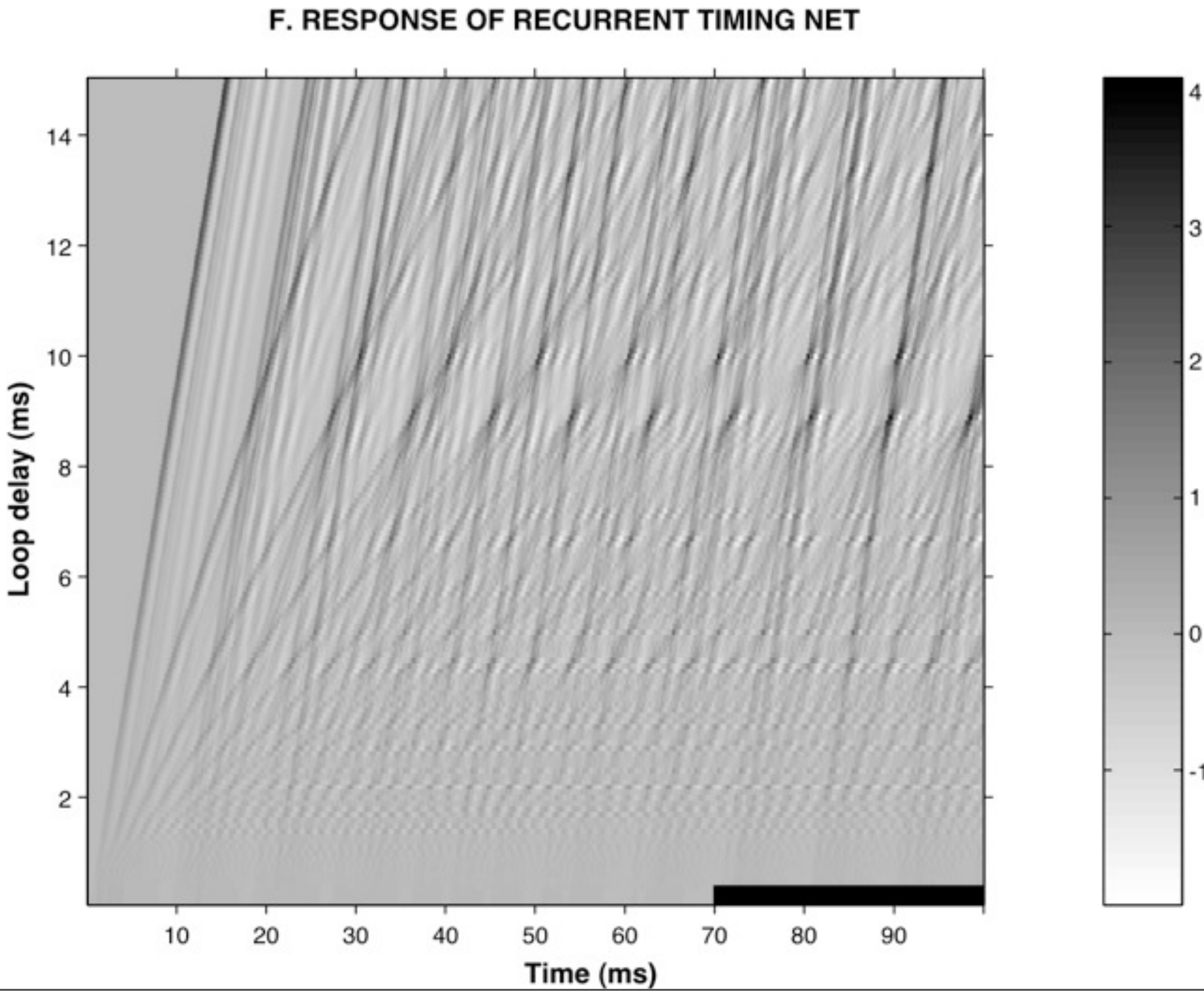
Error-adjustment rule:

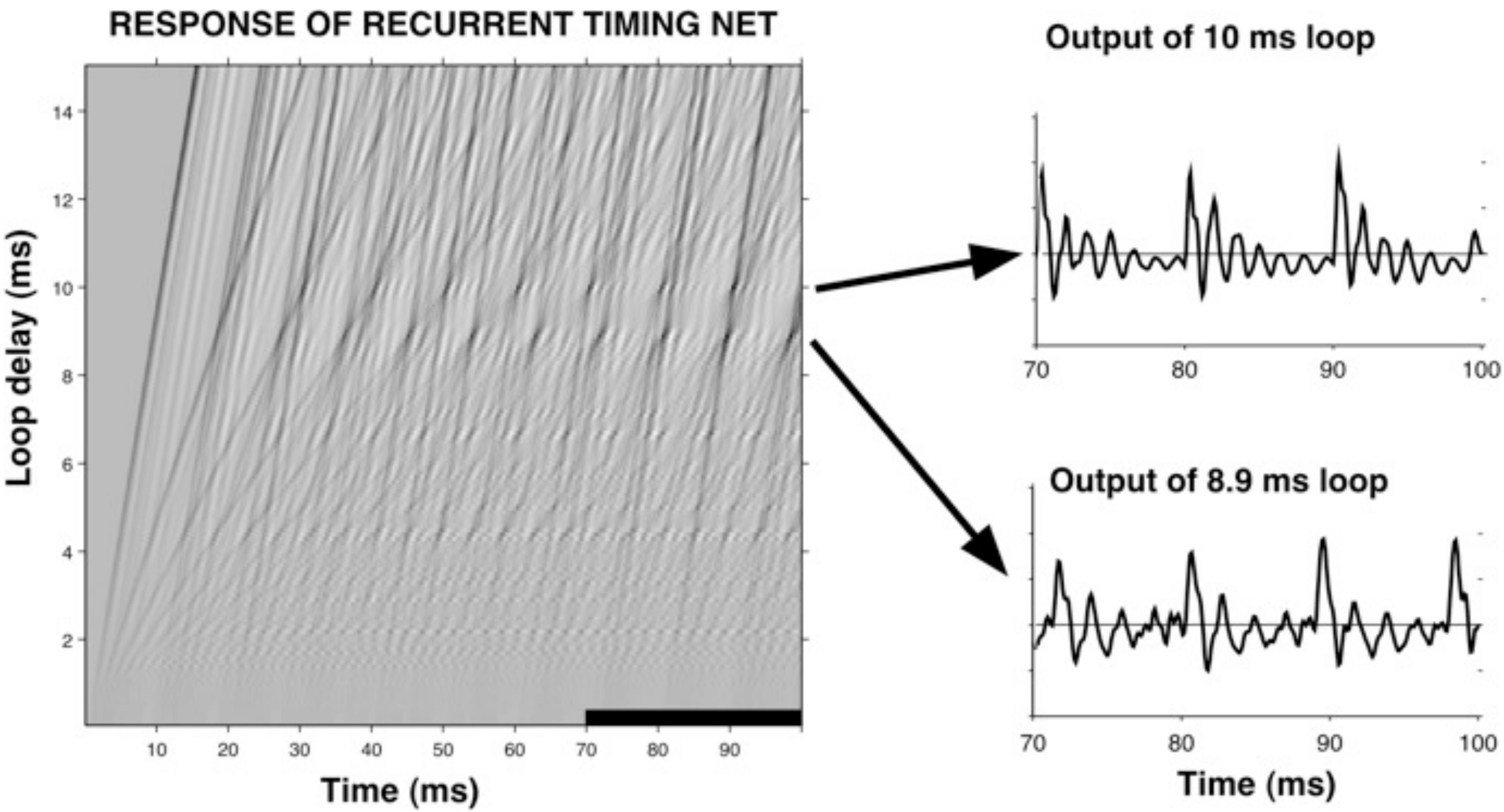
$$H(t) = H(t\text{-}tau) + B_{tau}[X(t)\text{-}H(t\text{-}tau)]$$

Loop-dependent scaling of adj rate:

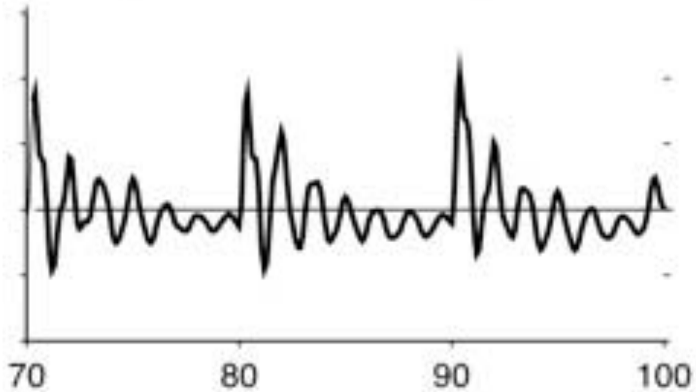
$$B_{tau} = tau/33\ ms$$



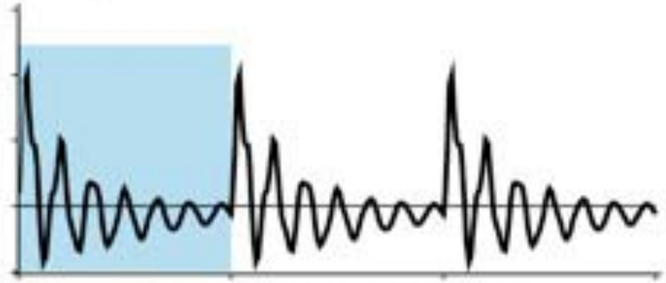

F. RESPONSE OF RECURRENT TIMING NET
Loop delay (ms)
Time (ms)
14
12
10
8
6
4
2
10
20
30
40
50
60
70
80
90
4
3
2
1
0
-1


RESPONSE OF RECURRENT TIMING NET
Loop delay (ms)
14
12
10
8
6
4
2
10
20
30
40
50
60
70
80
90
Time (ms)
Output of 10 ms loop
70
80
90
100
Output of 8.9 ms loop
70
80
90
100
Time (ms)

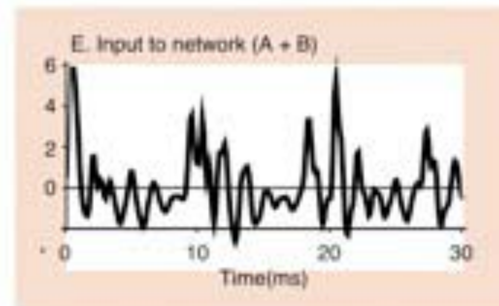
Output of 10 ms loop



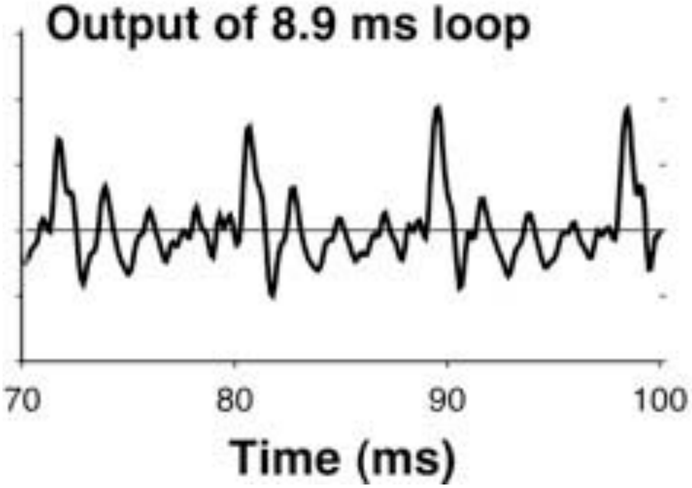
Original individual vowels

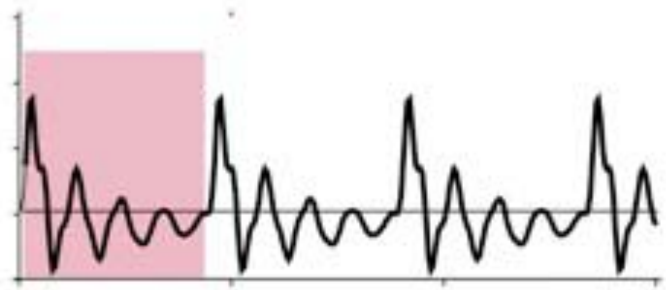


Vowel /ae/   F0=100 Hz



Output of 8.9 ms loop



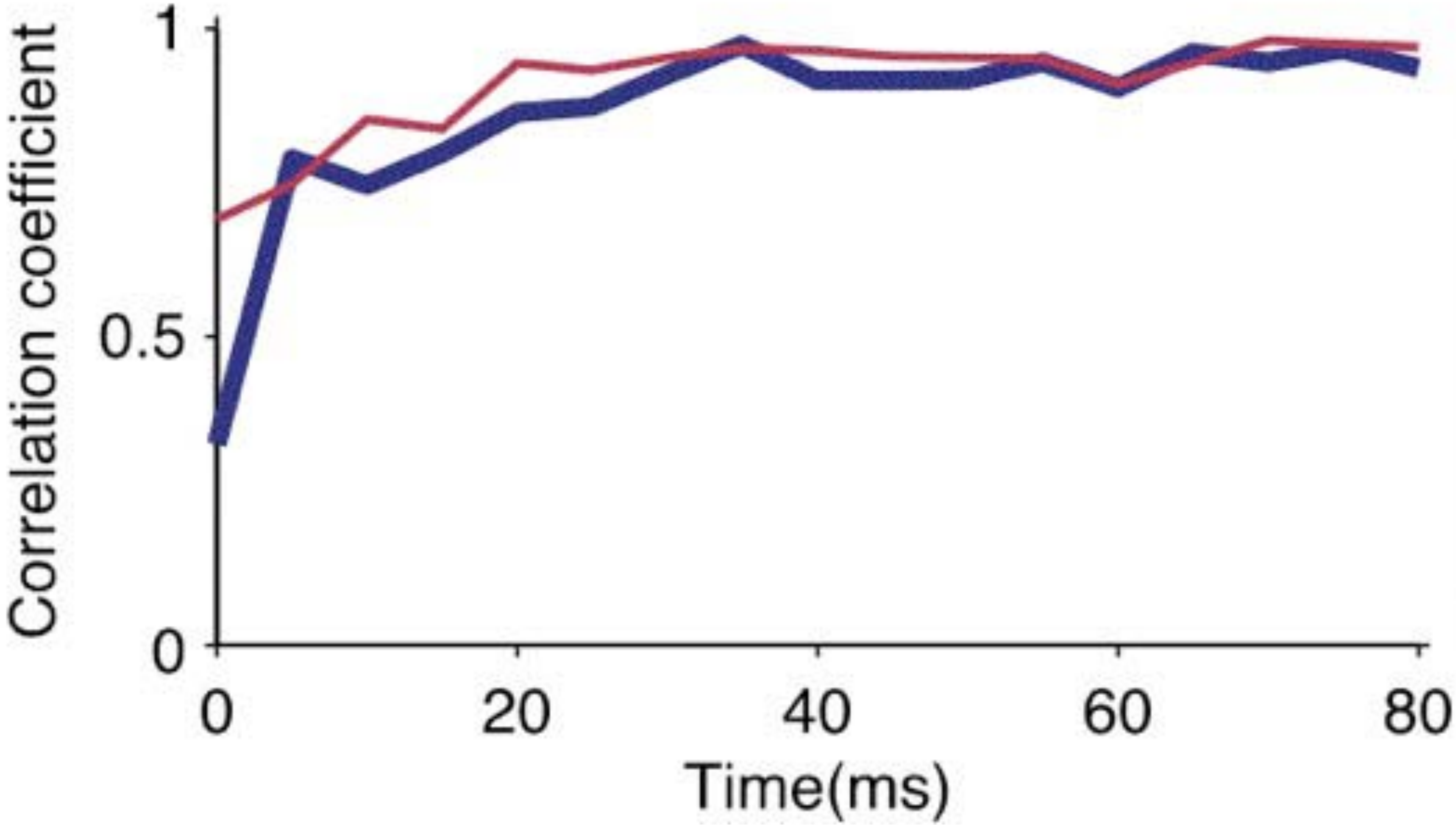


Vowel /er/   F0=112 Hz

Correlations of loop outputs to individual vowels

Correlations between autocorrelations

Thick: 10 ms loop waveform vs. /ae/
Thin: 8.9 ms loop waveform vs. /er/



Tonal & rhythmic contexts

Tonality induction:

- establishment of a tonic
- establishment of tonal system: key, mode, set of pitches
- establishment of harmonic relations

Western tonal music:

Relations of notes to the tonic

Relations of notes to the triad that defines the key (I)

- harmonic center

Relations of chords to I triad & tonic -- chord progressions

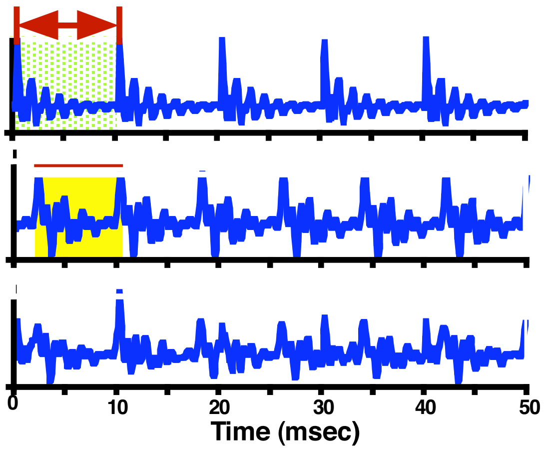
- Distance in perceptual similarity
- Tension-resolution + movement between the two

Relations of different keys and key modulations

- Movements between keys, tension-resolution, larger structures & rhythms of harmonic movement

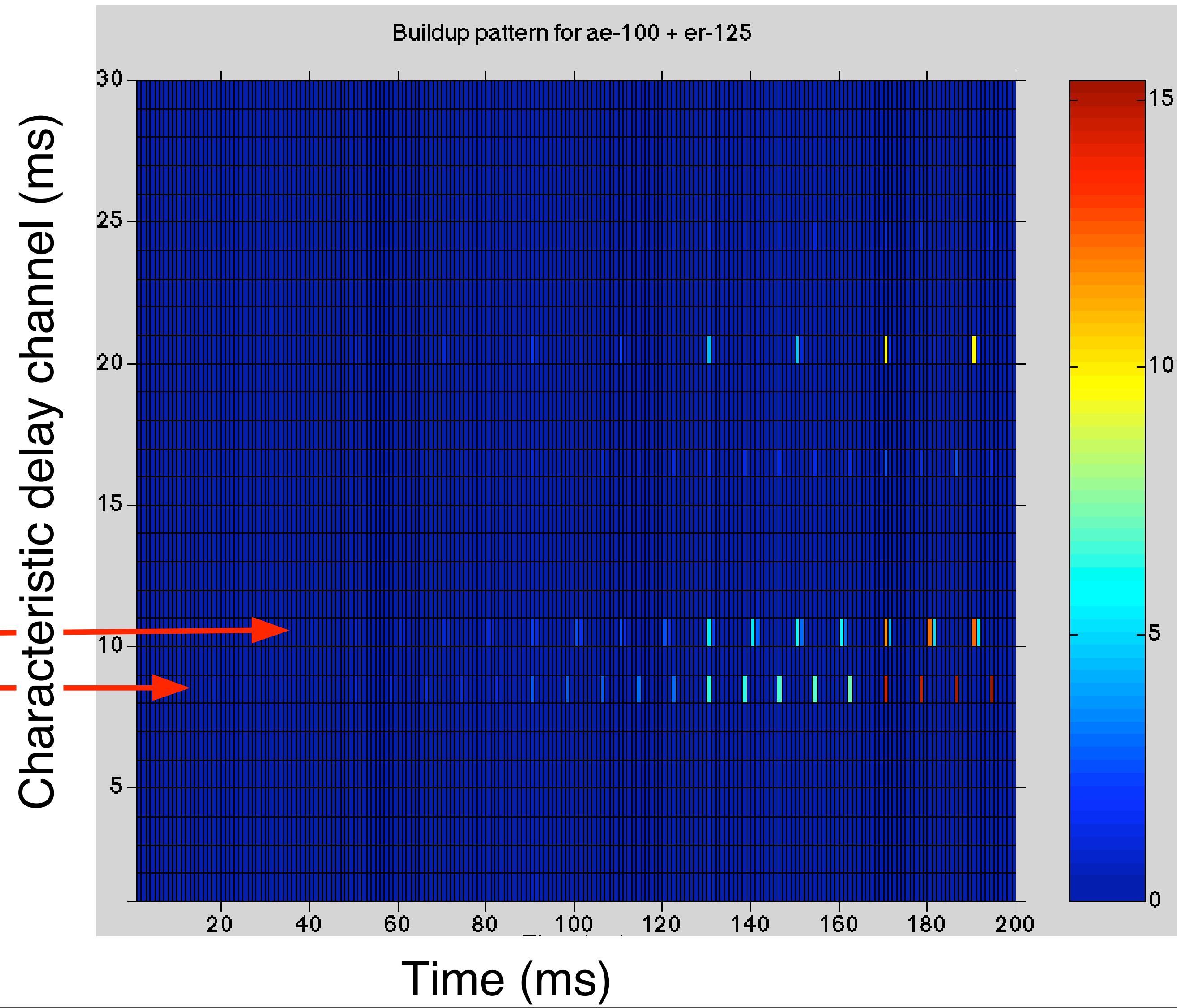
Build-up and separation of two auditory objects

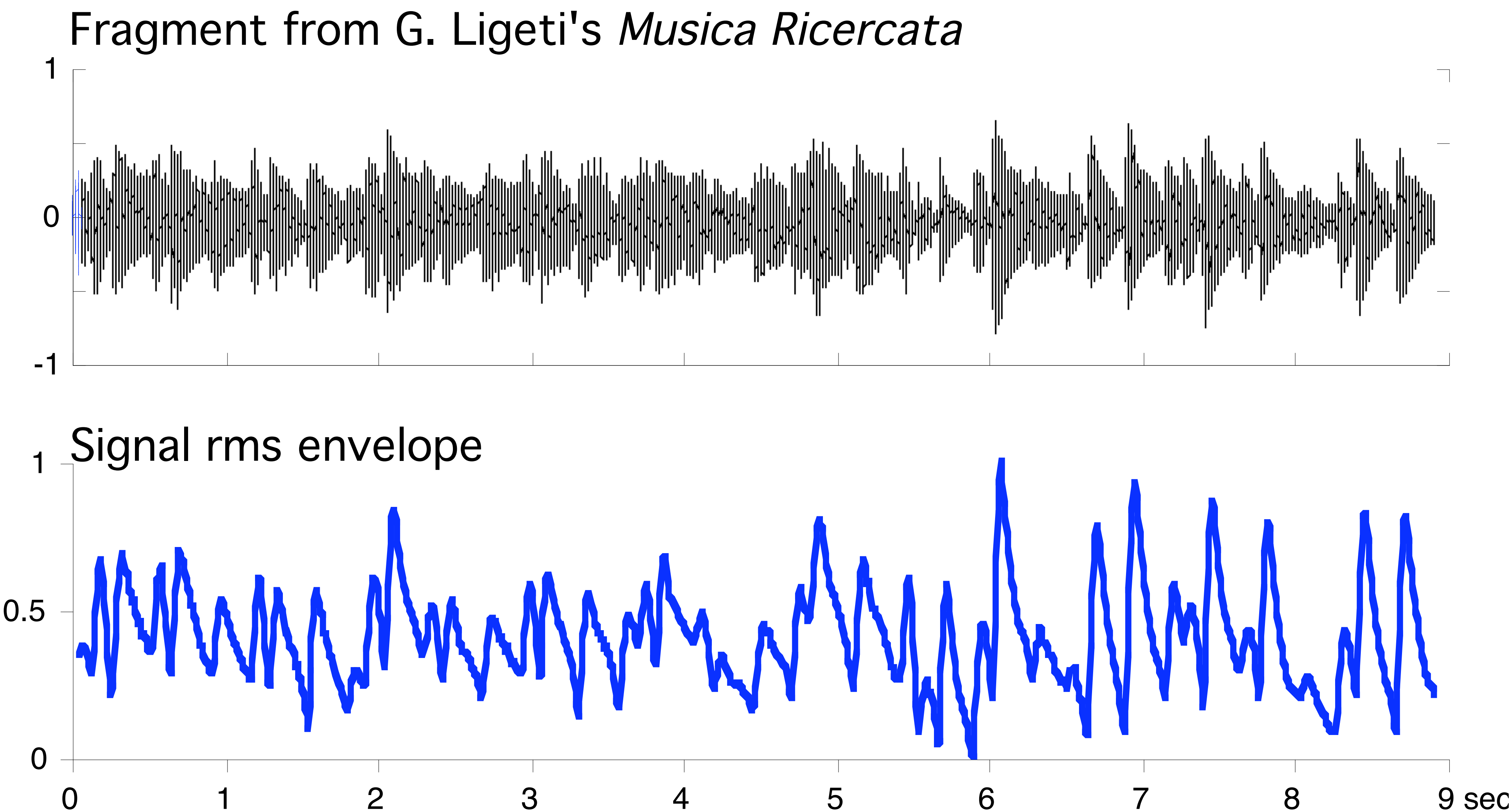
Two vowels with different fundamental frequencies (F0s) are added together and passed through the simple recurrent timing net. The two patterns build up In the delay loops that have recurrence times that correspond to their periods.



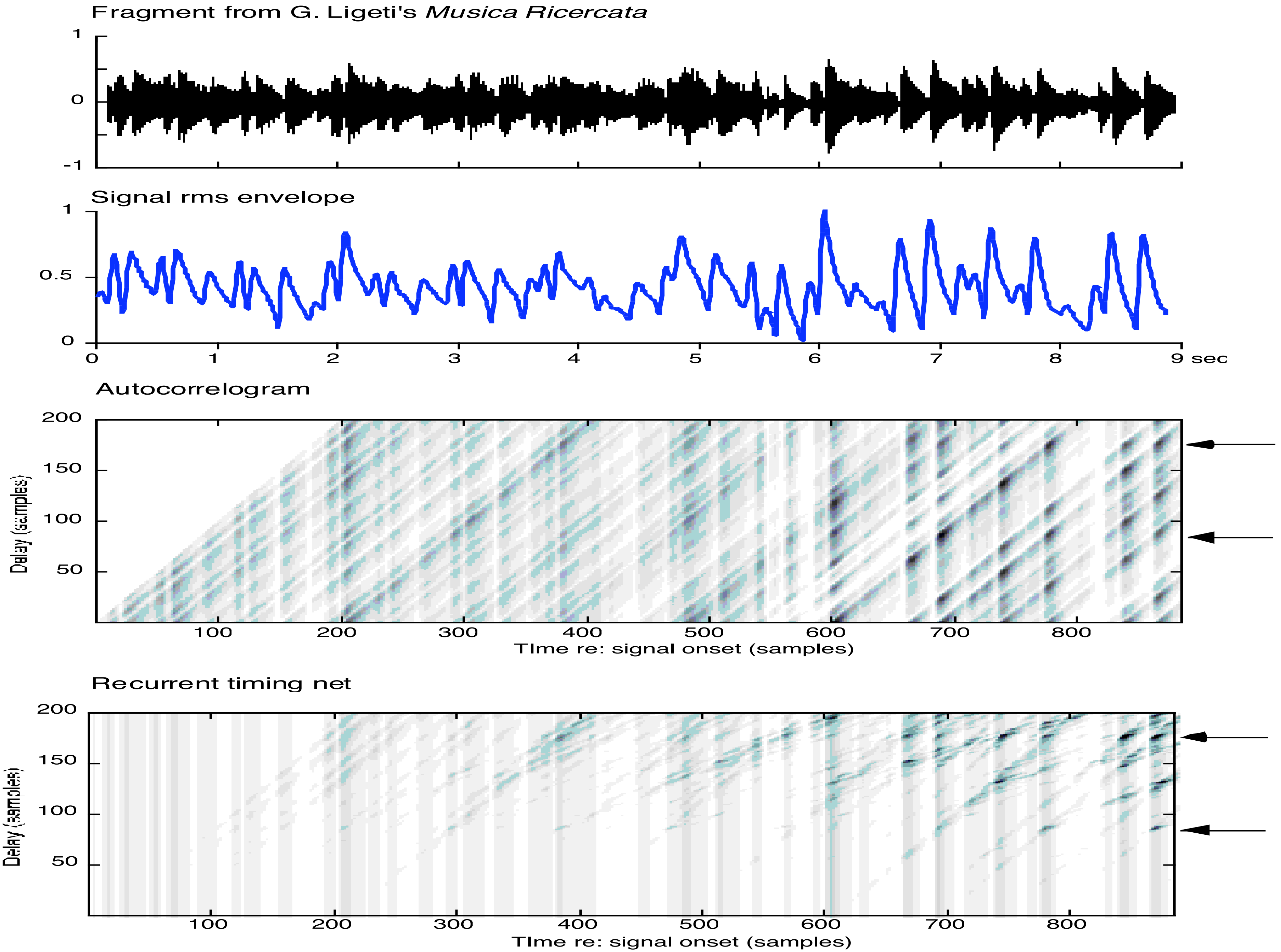
Vowel [ae]
F0 = 100 Hz
Period = 10 ms

Vowel [er]
F0 = 125 Hz
Period = 8 ms

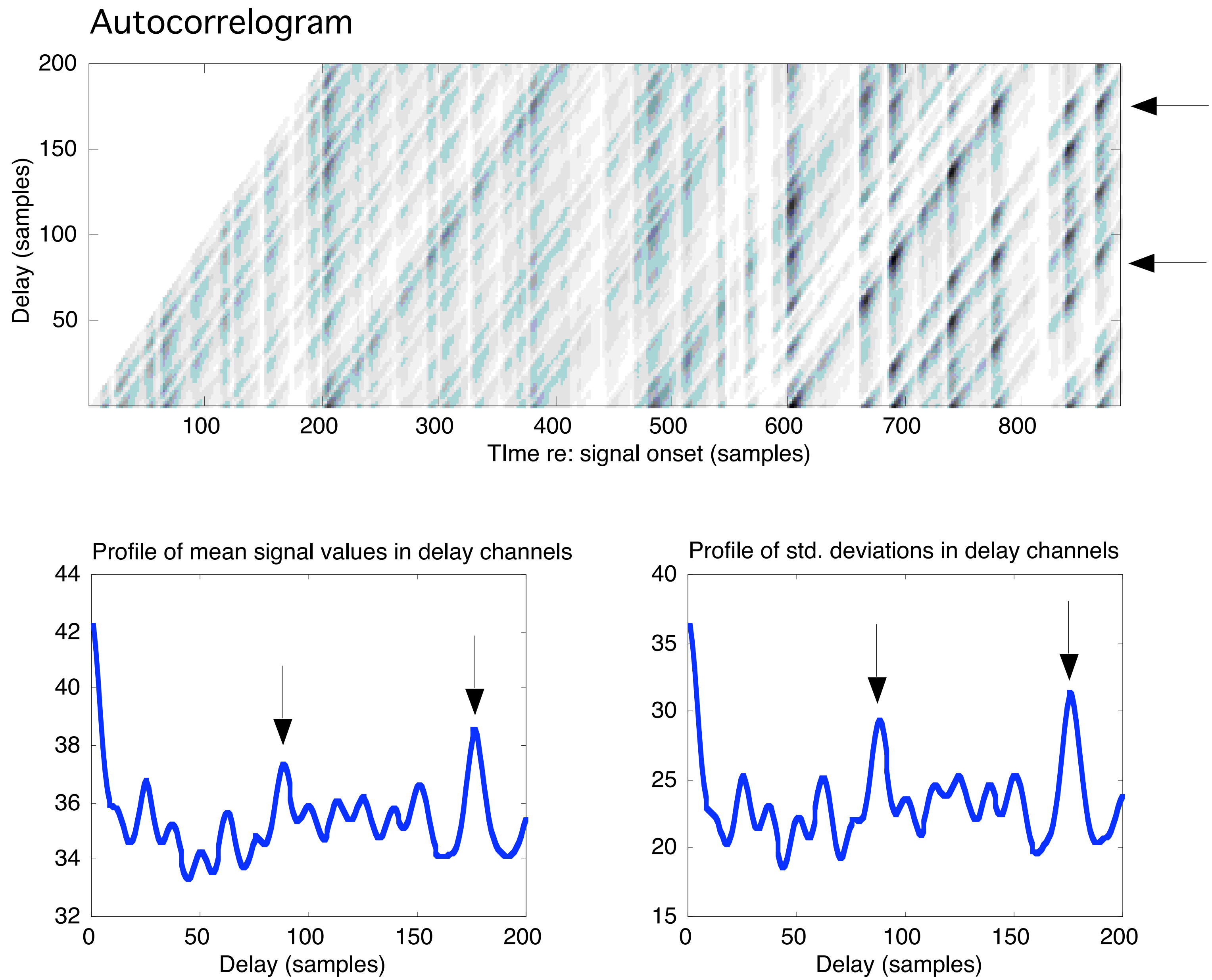




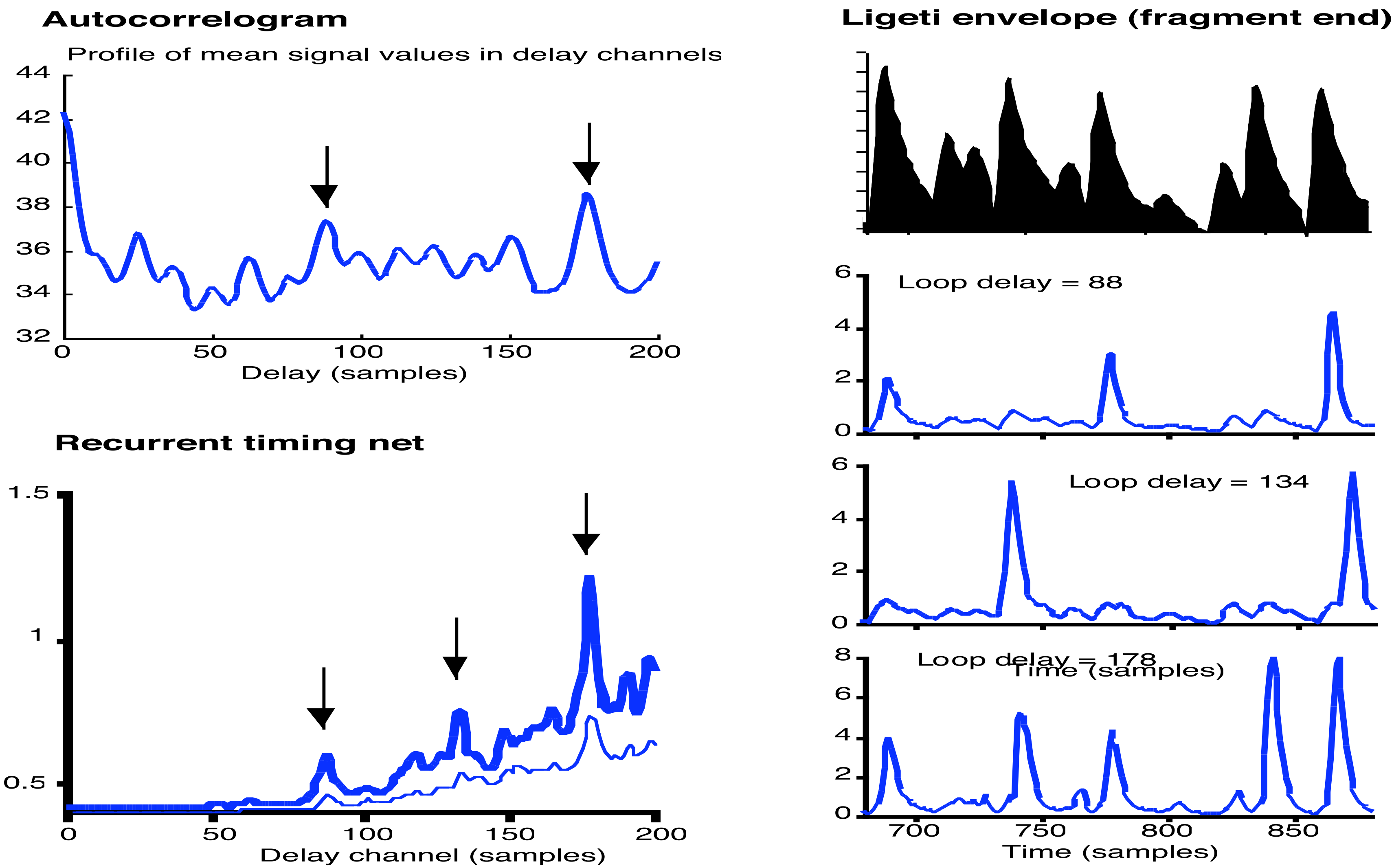
This image is from the article Cariani, P. "Temporal Codes, Timing Nets, and Music Perception." *Journal of New Music Research* 30, no. 2 (2001): 107-135. DOI: 10.1076/jnmr.30.2.107.7115. This journal is available online at http://www.ingentaconnect.com/content/routledg/jnmr/



This image is from the article Cariani, P. "Temporal Codes, Timing Nets, and Music Perception." *Journal of New Music Research* 30, no. 2 (2001): 107-135. DOI: 10.1076/jnmr.30.2.107.7115. This journal is available online at http://www.ingentaconnect.com/content/routledg/jnmr/



This image is from the article Cariani, P. "Temporal Codes, Timing Nets, and Music Perception." *Journal of New Music Research* 30, no. 2 (2001): 107-135. DOI: 10.1076/jnmr.30.2.107.7115. This journal is available online at http://www.ingentaconnect.com/content/routledg/jnmr/



Response of a recurrent timing network to the Ligeti fragment. H(j,i +j) = max (X(1,i), X(1,i)*H(j,i)*(1+j/100)) where X is the in envelope of the Ligeti fragment, and H is the value of the signal in delay loop j (firs index) at time t (second index). The buildup factor (1+j/100) depends on the duration of the delay loop (i.e. equal to j samples). The mean signal value H in the delay channels over the last 200 samples (thicker line) and over the whole fragment (thin line) are shown in the top right line plot. The waveforms that are built up in the three most activated delay loops are shown above. The results, not surprisingly resemble those obtained with the running autocorrelation. The sampling rate of the signal was approximately 10 Hz.

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