リズム研究

The Journal of Rhythms

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Recent Neuroscientific Research in Musical Rhythm: Excerpt from *Hearing in Time*, 2nd Edition, Chapter 3: The Neurobiology and Development of Rhythm （邦訳：音楽のリズムに関する最近の神経科学的研究について～『Hearing in Time』第二版、第三章「神経生物学とリズムの発達」より抜粋～）

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This chapter introduces the reader to recent research in brain science that sheds light on neurobiological underpinnings of musical rhythm. It presumes that the reader is already aware of (a) the distinction between rhythm and meter, and (b) the argument that musical meter is best regarded as a form of *entrainment*. It will be helpful, therefore, if we review these two points first.

First, rhythm versus meter (N.B., for a fuller discussion, see London 2001). *Rhythm* involves actual, real-world durations or temporal intervals and their organization into groups. For example, musical rhythms are often categorized as analogues to the feet of poetic versification: a short note followed by a long note is an iamb; a long-short-short is a dactyl, and so forth (e.g., Cooper and Meyer 1960). It should be noted that these patterns do not depend on the sustained duration of each note, as a rhythmic pattern can be played legato or staccato while retaining its identity. Thus we gain a sense of rhythmic shape from the inter-onset interval (in music psychology this is often abbreviated as "IOI") between the attack points of successive tones or percussive sounds. While rhythm involves the timing of phenomenal events—sounds in the world—*meter* arises from our perception of those rhythms. Meter is a mental phenomenon, a perceptually emergent aspect of our musical experience. Meter involves both the interpretation of events in the moment (e.g., "that is the downbeat") as well as our anticipation(s) regarding the temporal location of future events. While rhythm is bound up with durations, meter involves hearing beats and their organization into recurring cycles, what we commonly refer to as measures. While we often think of beats in relation to durations within a particular meter—4/4 time involves four quarter-note beats per measure—a moment's reflection will allow one to see that the "beats" in this measure are not a quarter note in length. Indeed, they have no real duration at all(!). Rather, they are the locations in time where (or more precisely, when) we expect the note onsets to occur.

Entrainment, loosely speaking, may be thought of as the temporal coordination between two or more regular temporal processes. Entrainment occurs in many contexts, from matching your stride rate to someone you are walking with to the synchronization of flashes amongst groups of fireflies; it is not a capacity unique to humans (though it does seem to be unique to humans among primates and other higher animals), nor is it uniquely musical in its origin. More strictly speaking, biological entrainment may be defined as the way that "in response to a periodic input, a physiological rhythm may become entrained or phase-locked to the periodic stimuli. In this case, there is a periodic rhythm so that for each N cycle of one rhythm there are M cycles of the second rhythm" (Glass and Mackey 1988, p. 13). This describes the relationship between two self-sustaining oscillators (or oscillating systems). The "periodic input" in our case is the music, whether produced by another person or by a mechanical or electronic device, while the "physiological rhythm" is the listener's metric response. In response to a series of drum beats we may tap our toes at the same rate, with little if any conscious thought; in hearing a Strauss waltz, we may feel ourselves moving in triple time along with the music, a more complex relationship between the rhythmic stimulus and our metrical response. And just what is synchronized through the process of entrainment? The answer is that it is our sensorimotor system, which involves both our attention to events in the world as well as our capacity and preparedness for movement with them. How our brains do this is the subject of the following excerpt.

Rhythms in Your Brain

The previous chapter surveyed a large body of research in rhythmic perception and production—essentially, many careful observations of human rhythmic behavior. These studies have shown the range of rhythms we can gauge and discriminate, the kinds of rhythms we can produce, which rates of rhythmic activity we prefer, how well we can coordinate our rhythms with others, and so forth. All of this tells us what we can do, rhythmically speaking, but not why or how. In this chapter we will try to get a bit closer to the whys and hows of musical rhythm by looking at evidence from neuroscience, development (i.e., studies with infants and young children), and social psychology. These areas of research will help to complete our account of meter as a kind of sensorimotor entrainment, one that is grounded by our exposure to music in particular cultural contexts, and one that is essential to our social experience of music.

Neurological Correlates of Beat and Accent

To recapitulate, entrainment is a form of coupled oscillation or resonance: the

periodic behavior of one system, which can temporally modulate some aspect of its activity, is yoked to the periodic behavior of another. The brain is not one such system, but rather a combination of many, many such systems. As Large (2008) summarizes with respect to rhythmic entrainment:

> The basic idea is that when a network of neural oscillators, spanning a range of natural frequencies, is stimulated with a musical rhythm, a multi-frequency pattern of oscillations is established. Endogenous pulse is linked with the concept of spontaneous oscillation, generalized synchrony with entrainment, and metric accent structure with higher order resonances, found in nonlinear oscillators at simple integer ratios [p. 198].

Populations of neurons can fire in synchrony at regular intervals and are subject to input (from other neurons and/or sensory transducers) that can modulate their behavior. The output from a population of neurons can in turn affect the behavior of other neurons, and so forth. And we have a lot of neurons: one hundred billion (10^{11}) neurons, each with about seven thousand synaptic connections.

However, when one attempts to examine neuronal activity in the brain, at first it appears to be a blooming, buzzing confusion, as different areas of the brain are constantly active, even in the absence of sensory inputs (e.g., when we are asleep). Neuroscience tries to make sense of this confusion using a variety of approaches. First and foremost is a careful and detailed study of neural anatomy and physiology, noting not just the gross structure of the brain but the particular kinds of neurons present in different areas, as well as the types of connections and pathways between them. Another well-known approach involves the study of individuals who have lost function in specific parts of their brains from injury, disease, or congenital malformation. Most current studies, however, make use of noninvasive imaging or monitoring techniques to study the neural activity of normal, healthy participants. As Grahn (2009) notes:

> [Neuroimaging techniques] can be divided into those measuring the electric or magnetic fields generated by neuronal activity (electroencephalography [EEG] or magnetoencephalography [MEG]) and those measuring the hemodynamic or metabolic consequences of neuronal activity (positron emission tomography [PET] or functional magnetic resonance imaging [fMRI]). These two classes of techniques provide complementary data: EEG and MEG have superior temporal resolution and are useful for exploring the time course of neural activity, whereas fMRI and PET provide superior spatial localization, indicating where in the brain such activity is occurring [p. 252, note 1].

By carefully studying which areas of the brain are consistently active when a particular kind of stimulus or activity is present, neuroscientists have mapped which particular areas of the brain are involved in particular perceptual, cognitive, and motor tasks, as well as how areas of the brain are connected in carrying out those tasks.

EEG and MEG studies typically involve a network of electrodes placed on the scalp, each of which is sensitive to the activity of an area of neurons, especially those near the cortical surface. Because the electrical response to a single stimulus is usually not apparent, given the overall level of electrical activity in the brain, in order to measure EEG and MEG responses a stimulus is presented many times and the results are then averaged, filtering out noise components. A regular, repeating rhythm is an excellent auditory stimulus for these studies, and one can examine the characteristic response that occurs at the moment a stimulus is introduced (so-called phase locked or "evoked" activity) as well as event-related potentials (ERPs) that occur at various time lags after the stimulus onset. These later "induced" responses are thought to indicate higher-level brain processes involving cognition and memory, rather than the immediate registering of sensation.

Brochard et al. (2003) and Schaefer et al. (2010) have given neurological evidence of subjective metricization, as our imposition of a sense of accent on a phenomenally undifferentiated series of pulses is manifest in differentiated EEG responses, indicative of cognitive processing on different temporal levels. Using MEG, Snyder and Large (2005) were able to show how we maintain a sense of pulse and of relative accent even in the absence of an expected stimulus—precisely what one would require of an entrainment system, namely that its oscillations should be self-sustaining, at least for a short time in the absence of any external input. They presented their experimental participants with the patterns given in Figure 3.1.

Snyder and Large first presented participants with either undifferentiated isochronous tones or dynamically differentiated tones (i.e., the control conditions). They were able to show that the dynamic accenting ("binary control") led to a differentiated pattern of evoked responses than did the unaccented stimuli ("periodic control"). When they then omitted one of the tones in the binary condition—which is to say, over a course of many presentations they would sometimes omit either the loud or the soft tone and then average the response—the result was that the induced activity persisted even in the absence of expected tones yet still reflected the relative accent:

> We found that high-frequency auditory activity occurring around the time of tone onsets [reflects both] stimulus-driven and expectancy-based representations of a simple binary metrical structure. Induced activity showed activations that in some cases
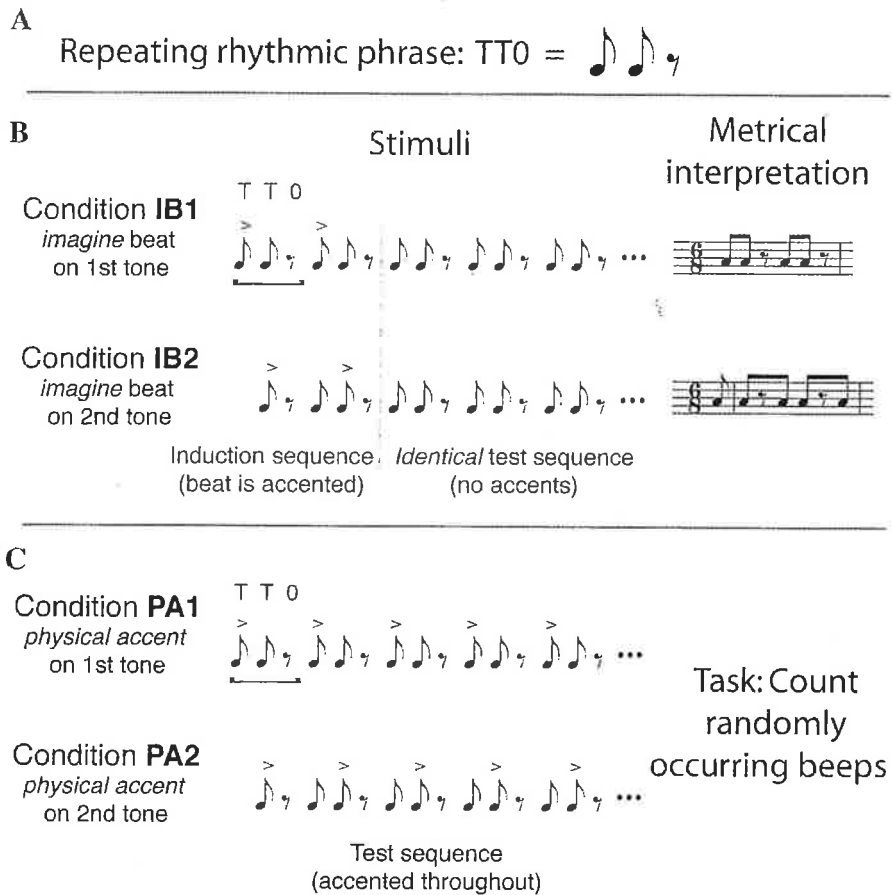
Figure 3.1. Stimulus conditions used in Snyder and Large (2005), figure 1, p. 119.
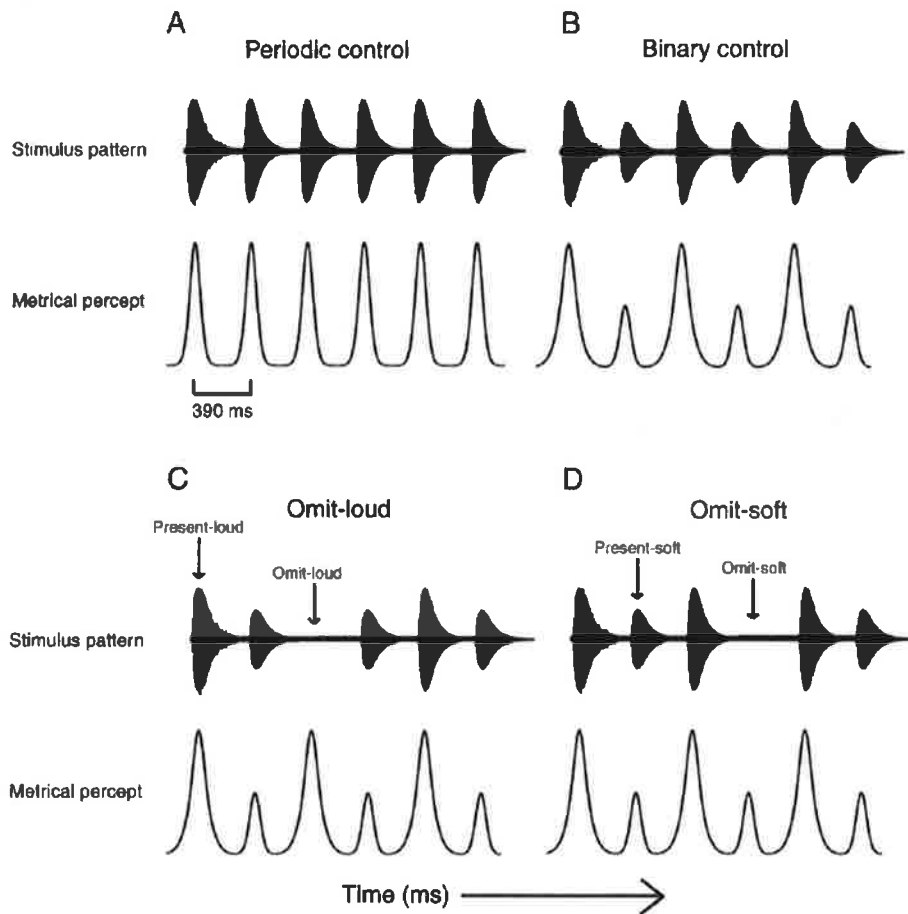
preceded tone onsets and showed very little diminution with omissions of expected tones. Evoked activity, on the other hand, showed a much stronger dependence on the physical presence of tones with larger responses to loud than soft tones and large diminution with tone omissions. These findings support current theories of meter perception that posit an active expectancy-based processing [Snyder and Large 2005, pp. 125–26].

In another MEG study, Iverson et al. (2009) extended Snyder and Large's findings using a paradigm that probed the effect of endogenous accent. They used a tone-tone-rest sequence, and the variable was whether the participants (as per instruction and contextual priming) were to hear the accent on the first or second tone (that is, a downbeat vs. anacrustic orientation of the rhythmic pattern, respectively). A diagram of their stimuli is given in Figure 3.2.

Figure 3.2. Stimuli used in Iverson, Repp, and Patel (2009), figure 1, p. 60.

A

Repeating rhythmic phrase: TT0 =

B

Stimuli   Metrical interpretation

Condition **IB1**
imagine beat
on 1st tone

T T 0

Condition **IB2**
imagine beat
on 2nd tone

Induction sequence   *Identical* test sequence
(beat is accented)   (no accents)

C

Condition **PA1**
physical accent
on 1st tone

T T 0

Task: Count
randomly
occurring beeps

Condition **PA2**
physical accent
on 2nd tone

Test sequence
(accented throughout)

The study had three main findings. First, the mechanisms involved in endogenous metrical interpretation have a strong modulatory effect on early auditory evoked responses, and this effect is temporally precise and specific in neural frequency. Second, simply imagining a tone to be the beat increased beta response in a similar way, as if that tone had been physically accented. Third, although beta responses (in the 20–30 hz range) reflect both imagined beat and physical accent, ERF (1–10 hz) and gamma-band (30–50 hz) responses reflect only the physical accent (Iverson et al. 2009, p. 68). As the authors suggest, brain activity in the beta range may thus play a special role in shaping both top-down (endogenous) and bottom-up (stimulus-driven) responses to rhythmic sounds; the induced beta response, which may be indicative of anticipatory attending, can increase the evoked response. In a similar study of missing beats Fujioka, et al. (2009, 2010) found that at lower frequencies (longer periods) entrainment seems to be more stimulus-driven, where at higher frequencies neural oscillations were more self-sustaining. Finally, in a perturbation study, where every sixth to tenth tone in an otherwise isochronous sequence came early or late, Zanto et al. (2005) found a pattern of induced gamma

band activity that mimicked the timing pattern observed in behavioral studies (e.g., Repp 2002; Large, Fink, and Kelso 2002).

Virtual Motion I: The Motor System

Although EEG and MEG studies have been able to show how brain activity can synchronize with external rhythms, as well as maintain endogenous rhythms independent of external stimuli, their ability to determine the loci of brain rhythms is limited, especially for subcortical areas of the brain. Whereas fMRI and PET imaging techniques do not have the temporal resolution of EEG or MEG, their excellent spatial resolutions have been used to determine which parts of the brain are involved in rhythmic perception and production.

Chen, Penhune, and Zatorre's 2009 article "Listening to Musical Rhythms Recruits Motor Regions of the Brain" essentially answers the question of rhythmic localization in the brain. The main areas involved are the basal ganglia, supplementary motor area (SMA), the premotor cortex (PMC), and cerebellum. The basal ganglia, which involve several related areas (the caudate, putamen, globus pallidus, and subthalamus) play roles in motor control and learning. The cerebellum is involved with the integration of sensory and motor information, and this allows the coordination and fine-tuning of movement. The PMC and SMA have many neural connections to the basal ganglia and cerebellum; these areas are involved in the executive functions of movement and action (for more specific citations, see Grahn 2009, pp. 258–59). Using fMRI, Chen, Penhune, and Zatorre (2008) found that the cerebellum, SMA, and mid-PMC were activated both when actually performing a rhythm and when passively listening to a rhythm. One confound is that these areas might also be involved in listening to nonrhythmic stimuli (i.e., in audition more generally). However, Bengtsson et al. (2009) in another fMRI study found that the dorsal PMC, SMA, and lateral cerebellum were more active when listening to rhythmic (regular) vs. random temporal sequences. SMA and pre-SMA areas also showed activity dependent upon temporal predictability (i.e., the motor timing and control areas involved in perception of temporal regularity).

In a PET study, Thaut et al. (2009) had their participants tap their fingers to a steady, randomly shifting, or smoothly accelerating or decelerating metronome. They found cerebellar activation present in all conditions, while subliminal versus liminal tempo modulations engaged different parts of the posterior lobe of the cerebellum. Cerebellar activation patterns corresponded to those in primary and secondary SMA areas in the cerebral cortex, which led the authors to posit that "distinct functional cortico-cerebellar circuits subserve different aspects of rhythmic synchronization" (p. 44).

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The basal ganglia have been particularly implicated in our sense of pulse or beat. Grahn and Brett (2009) found evidence of this by comparative study of rhythmic discrimination in Parkinson's patients versus normal control participants. They asked both groups if a target rhythm was the same as or different from a standard that was presented twice in succession. Some standards and targets had clear beats, while others did not. As Grahn and Brett predicted, even though Parkinson's patients did much more poorly in their discrimination of beat-based rhythms than normal control participants, both groups did about the same with the nonbeat-based rhythms. Parkinson's patients are known to have difficulty with motor control tasks, but here it was extended to a discrimination task with no overt motor requirements. As the authors note, "Given that Parkinson's disease affects the basal ganglia, this suggests that the basal ganglia are part of a neural system involved in the detection and/or generation of an internal beat, and that this system is compromised in Parkinson's patients" (p. 54). Grahn and Rowe (2009) manipulated the parameter that gave rise to a sense of beat and accent; in some stimuli, rhythmic figures were determined by relative length, in others by dynamic accent, as well as isochronous, dynamically undifferentiated control sequences. In all cases, robust activity occurred in the basal ganglia (specifically, in the putamen). In the unaccented beat condition some participants claimed to perceive more complex patterns of accent; as Grahn and Rowe aptly noted, "although the stimuli are quite simple, what participants 'do' with their perception may not be so simple" (p. 7546). They also propose that "the role of the basal ganglia in rhythm perception, as in other domains, is prediction: when a detectable structure is present in the rhythm, predictions can be made about the timing of future onsets. Successful predictions can enhance the speed of perceptual organization of the sequence, reducing working memory load" (p. 7547). In other words, greater predictability not only focuses attention (as per Jones 2001; Large and Palmer 2002) but also speeds the processing of expected events.

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While neuroscience and neurophysiology are still in their infancy, the research surveyed above provides direct evidence for rhythmic in the brain in response to external musical rhythms, which is to say, rhythmic entrainment. Moreover, these brain rhythms can be generated in the absence of overt auditory stimuli; simply *imagining* musical rhythms can generate the same kinds of brain activity. This research also shows that rhythm and movement are bound together because our faculties for rhythmic perception are intimately linked to our sensorimotor system. Bruno Repp hypothesized that "metrical interpretation rests on covert rhythmic

action" (Repp 2007 p. 434); neuroimaging studies have made this covert action overt. Thus when we say that a piece of music "moves us," we are not speaking metaphorically, but literally, because to hear a rhythm is to hear motion.

When we engage with musical rhythms, we move with the music, but only in certain ways. While psychological and neurobiological studies of musical rhythm are fascinating in their own right, and tell us much about the workings of the human mind, for the musician and music theorist they also tell us about the kinds of rhythms we can (and cannot) hear and perform. As one of the central concerns of rhythmic theory is to delimit the range of well-formed versus malformed rhythms and meters, psychology and neurobiology help to stake out the limits of metrical well formedness, with the added benefit that these limits are not yoked to any particular musical culture or style. This allows one to pursue more general/universal aspects of musical rhythm and meter, as well as better understand their workings in any particular musical context, from American jazz to Japanese Gagaku. The exploration of metrical well-formedness, and its manifestation in a broad range of musical cultures is the concern of the remaining chapters of *Hearing in Time*.

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