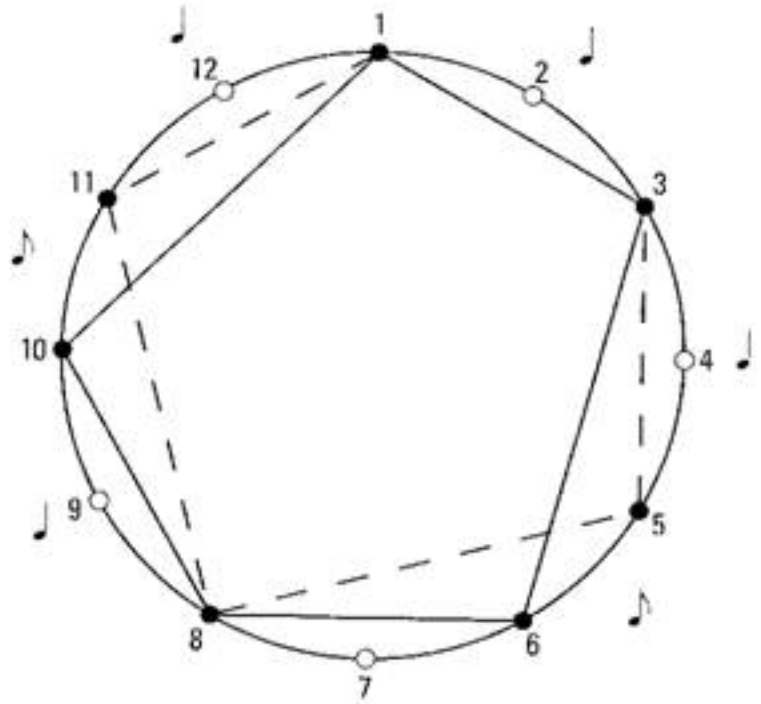
How to Talk About Musical Metre
UK Lectures Winter & Spring 2006
Justin London



Abstract

What is a beat? And what makes a rhythmic or metric pattern "regular"? While musicians and music theorists have strong intuitive notions about beats and regularity, and can find ready illustrative examples in their native musical practices, understanding their roots and causes is often more difficult to pin down.

A deeper understanding of meter may be obtained (a) by taking into account the experimental literature on human temporal perception, cognition, and rhythmic behaviour, as well as (b) by looking at rhythm and meter in Non-Western musical cultures.

The paper begins with a presentation of psychological research that sheds light on the nature of beat perception, especially with regard the temporal limits for rhythm and meter. Our perception of a metrical beat is shown to be a kind of *entrainment*, a musically-specific form of our more general capacity to synchronize our attention and/or motor behaviour with temporally regular events. I then turn to rhythmic and metric regularity in a few examples from Africa and North India. Parallels are drawn between the non-isochronous beat patterns in these music and the uneven beats present in rubato performances of Romantic piano music. These examples of "uneven" rhythms lead to a discussion the principle of *maximal evenness,* which, it is argued, underlies rhythmic and metric patterns that we regard as regular.

1. What is Meter?

To understand what meter is, let us first make clear what meter is not. Meter is not an aspect of musical notation, such as a time signature or a mensuration:

While these markings may have (and usually do have) metric significance, in that they direct the performer to play or sing the given pattern of durations in a particular way, they are merely means to a metric end. To put it another way, as every musican knows, meter is *how* you count time, and rhythm is *what* you count--or what you play while you are counting.

But listeners also have a sense of meter (whether they are manifestly counting or not)--it is that keen sense of when something is going to happen, of whether a note comes early or late (or not at all). Both listeners and performers know that if a piece has a stable meter, their counting/expectations remain steady, even if the melodic and rhythmic figures may vary.

What is perhaps the cardinal sign of meter is that it is both produced by (and once established, gives rise to) a sense of beat or pulse. Indeed, because beats are so central to meter, we may define meter in terms of them:

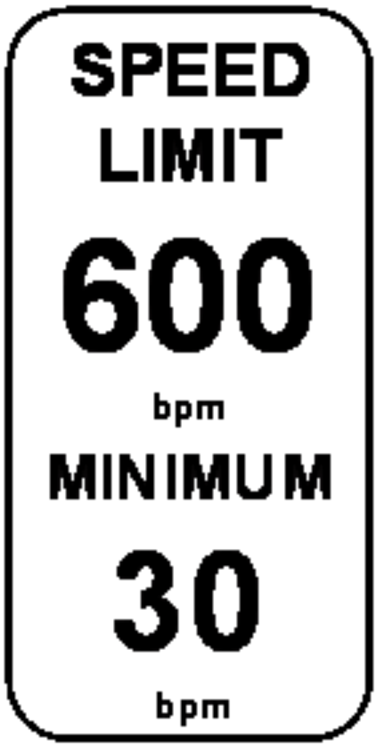
> Meter is the presence of a regular pattern of beats.

Of course, this leads to two more questions: *What is a beat?* and *What makes a pattern "regular"*? To answer these latter questions, we will turn to perceptual psychology (for beats) as well as the cross-cultural study of musical rhythm (for regularity). In doing this, we will approach meter from the listener's perspective, for as will be argued, beats are a phenomenal aspect of our musical perception—they are not simply the loudest events in a group of notes, or even congruent with the onset of a sound. Rather, beats are the product of our interaction with certain kinds of rhythms in the environment.

2. The limits of rhythmic perception :

To understand our perception of beats we must first understand the limits of our temporal perception more generally. As composers and performers have long known, one cannot hear a sense of beat (as well as a sense of a rhythmic pattern) if the note onsets are too far apart (i.e., it is too slow) or, conversely, if the pattern is so fast the notes blur together as in a trill or glissando.

There are, then, speed limits for the perception of rhythm and meter:



AKA

There is converging evidence from studies of temporal perception, memory, and rhythmic performance that show that these maxima and minima apply for musical rhythm. The "rhythmic ceiling" (the fastest/shortest elements that can be involved in rhythms and beats) seems to be around 100 milliseconds (ms) for most listeners:

- At 100ms, as opposed to shorter durations/interval onsets, a difference in the detection of asynchronies and lengthening of elements in a series of six tones becomes apparent (Hirsh, Monohan, et. al. 1990)

    To hear a demonstration of this experiment, First click HERE (use the "back" button on your browser to return to this webpage after you have listened). You will hear a two "click trains" at a baseline IOI of 70ms. In the first train the last click is late, while in the second it is early. Can you tell? Now click HERE. Again, you will hear a similar pair of click trains, but now the baseline IOI is 120ms. Now can you tell the difference?

- In a study of jazz drummer's ride cymbal patterns, 100ms functions as an absolute limit on the product of short, rhythmically salient durations (i.e., the Short element in a Long-Long-Short pattern can only get so short—Friberg and Sundstrom 2002)
- In a clever tapping synchronization study, Bruno Repp (2002) had his subjects to every 2nd, 3d, or 4th of a rapid series of metronome clicks. In this way he avoided running into motor limits on the rate of tapping, but could still probe the rate of synchronization for thes rapid "subdivisions" of a slower level of pulses. Repp noted that

This task requires a subjective organization of the tones into groups of four, as investigated long ago by Bolton (1894). On the basis of introspective reports, Bolton estimated that subjective grouping of sounds becomes difficult at IOIs of 158 ms and impossible at IOIs of 115 ms. The latter estimate is in good agreement with the average auditory synchronization threshold found in the present study (Repp 2002)

What is apparent is that once the inter-onset interval ("IOI") between rhythmic stimuli (whether they are notes or drumbeats or metronome clicks) is greater than 100ms, it becomes possible for listeners to hear these notes or clicks as elements in a rhythm—as quadruplets and sextuplets. And moreover, we are able to note differences in length, and thus tell whether a rhythmic figure is composed of even or uneven durations. In short, we are able to make judgements of quantity and duration only when the IOIs are longer than 100ms (i.e., slower than 10 per second).

But the IOIs for notes or drumbeats can't get too slow, either. Other studies have shown that if the IOIs are greater than 1.5-2.0 seconds, the rhythm falls apart. This, then, is the other boundary of our rhythmic and metric speed limits. Here is a simple demonstration of this limit.

First, listen to a rhythmic figure, known in North America as "Shave and a Haircut . . . two bits" ("two bits" is an archaic term for twenty-five cents, and of course it has been a long time since one could get a shave and a haircut for that price).

Shave and a Haircut—normal speed.

Note that you have no trouble anticipating when the "two bits" will occur. Listen again to a slower version of the pattern:

Shave and a Haircut—slowed down.

Though this is now an adagio shave, you still can find the two bits. But if we take it down even more (making the baseline interval greater than two seconds), you can't find the bits:

Shave and a Haircut—too slow.

The two second limit is well documented in the research literature. Here are a few examples:

- If you ask someone to produce a "comfortable beat" (neither too slow or too fast) one most often gets responses in the range of 500-700ms (120-86 beats per minute). This is known as "spontaneous tempo," and has long been studied (James 1890). The upper limit for spontaneous tempo is 1.5-2.0 seconds.
- Similarly, if one is presented with just a series of clicks or beats, even if they are phenomenally identical, we tend to hear them in groups of twos, threes, or fours. This is know as "subjective rhythmicization," though subjective metricization might be a better term. Subjective rhythmicization has also long been studied (see Fraisse 1982 for a summary), and it too occurs only when note IOIs are 1.5-2.0 seconds or shorter.
- At about 1.5-2.0 seconds, studies have noted a shift in synchronization behaviors (Woodrow 1932). Empirical studies have shown that when you tap along to a metronome, when you steadily keeping time you are actually a bit ahead of the beat (20-40ms). We don't usually notice this anticpatory syncrhonization error (or negative asynchrony, as it is also known), but believe that we are keeping time more or less exactly with the pacing metronome. However, if the beat slows down below 40 beats per minute or so, the anticipation disappears, and we begin to tap behind the beat. Moreover, if the beat is then perturbed, we no longer notice, for instead of tapping in synchrony, we now perform what is essentially a reaction-time task.

3. Meter as Entrainment, and Beats as a Result

Our metric engagement with regular rhythms (both musical and non-musical) is active, not passive. Here is the opening from "I'm Your Hootchie Cootchie Man" by Muddy Waters:

Hootchie Cootchie—Loop

This song begins with a paradigmatic example of the "stop time" ostinato that is often used in jazz and blues. The accompaniment plays a figure last beat of the beat of the measure, and into the downbeat of the next--and then stops. The listener must interpolate the missing beats (the second and third beats of the measure) in the intervening silences. Things get even more complicated once Muddy Waters starts Singing:

Hootchie Cootchie—Excerpt

Now one must interpolate the missing beats against the “rhythmic interference” of the vocal part, as it is patterned on the speech rhythms, with slight timing accommodations for the music at the end of each phrase. While some parts of "Hootchie Cootchie" are regular, others are not. It is a more typical example of what we do when we listen--we fill in missing elements (in this case, a lot of missing elements), and accommodate various forms of rhythmic “noise” to preserve our sense of regularity.

“I’m Your Hootchie-Cootchie Man” illustrates our response to regular rhythmic stimuli in our environment. This response, beyond just a musical context, is known as entrainment:

In response to a periodic input, a physiological rhythm may become entrained or phase-locked to the periodic stimuli, such that for each N cycles of the input there are M cycles of the second rhythm.” (after Glass and Mackey 1988

Provided the periodic stimulus occurs within our 100ms to 2.0 second range, and provided it is regular enough (more on that below), we will reflexively entrain to it. Musical meter is, quite simply, entrainment in a musical context. What exactly is entrained? A: our attention, minimally, as well as our motor behaviors. Our attention, in that meter involves our temporal expectations, and our motor behaviour, either overt or covert, in that such expectations guide the timing of our actions (so that we tap our toes or play our piano keys at just the right moments).

Our sense of beat or pulse is a by-product of entrainment. When we are entrained to a rhythmic process, our “internal oscillators” generate peaks of expectation and motor priming. Subjectively these are felt/experienced as beats (especially noticeable when phenomenal articulations are absent in the music!).

A few other points:

- Metre involves not just a single periodic stimulus, but a coordinated set of attentional periodicities—different levels of temporal regularity—which may (and usually do) direct our attention and motor behaviors.
- Metres —as attentional and motor behaviors—are distinct from Rhythms, which are the patterns of duration that occur in the music.
- Our metric behaviors are highly practiced. We have been listening to rhythmic stimuli since birth (indeed, since before birth), and of course have been walking and talking for most of our lives. So the fact that most listeners are "rhythmically expert" should be taken into account (and this may also explain the results of various studies of rhythmic perception and behavior which often show little or no difference between musicians and non-musicians).

4. Regularity

What, then, about regularity? The first point is that repetition, while necessary, is not sufficient to give rise to entrainable regularity:

Tangle Eye Blues

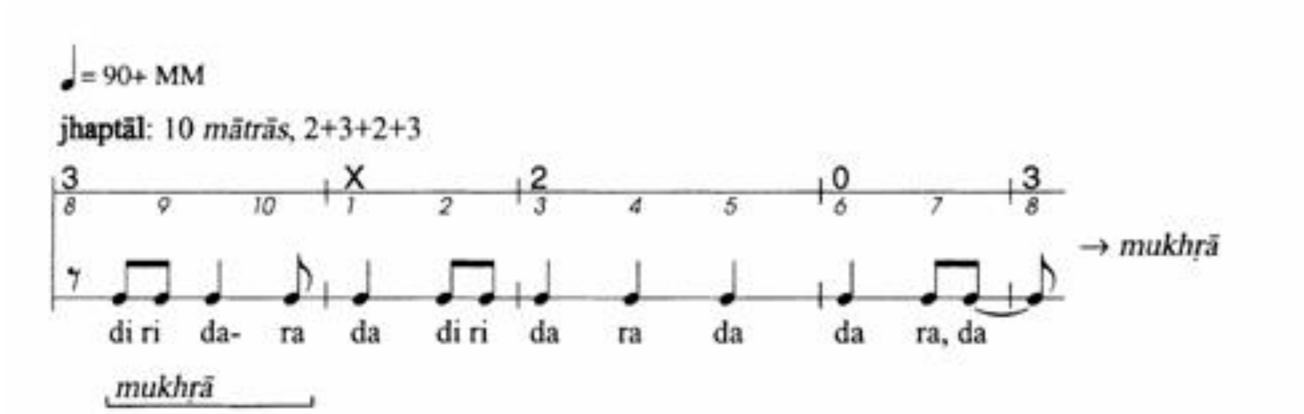
This example, “Tangle Eye Blues” (recorded by Alan Lomax on the notorious Parchman prison farm in Mississippi) is a haunting blues holler. Melodically it is based on the repetition of a basic motive for both the vocalise and texted phrases. But it isn’t quite fast enough, or continuous enough, to give rise to a sense of pulse (or at least a robust, sustained sense of pulse). So entrainable rhythms have to be both repetitive and continuous in order to create a sense of pulse. But the repetitions do not have to be exact, or to put it another way, the beats do not have be isochronous:

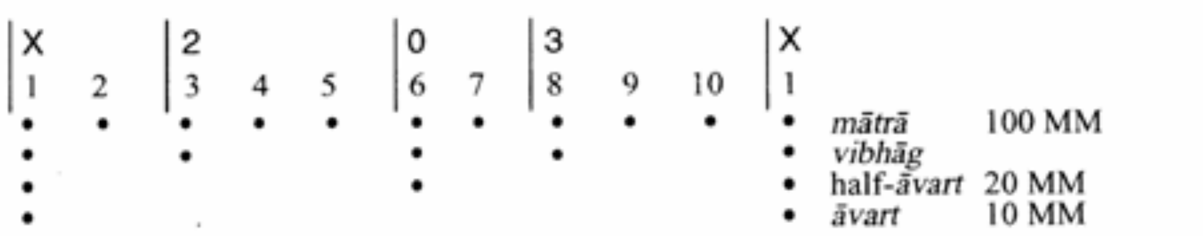
A "Standard Pattern" for the Bell in West African Music

This example, of a typical bell pattern in Ghanaian music, has a rhythmic surface that can be construed in various ways. While some have argued that this should mainly be heard in terms of four even beats in a 12/8 meter (Agawu 2006), it is also possible to hear an uneven series of 5 beats (in the proportion 2+2+3+2+3). Under the latter hearing, the beat level is non-isochronous.

Here are two examples from Nketia (1963): (a) Akatape Dance (b) Akan Dance. Both use the same bell pattern that was given in the sound file above. Note that (a) the bell pattern is played as an accompaniment, along with other instruments, to the songs, and (b) just as in western music, the relation between the rhythm and meter is less than obvious. That is, the melody does not dictate the meter, but is rhythmically and metrically supple.

Here is another example of a non-isochronous meter, from northern India:

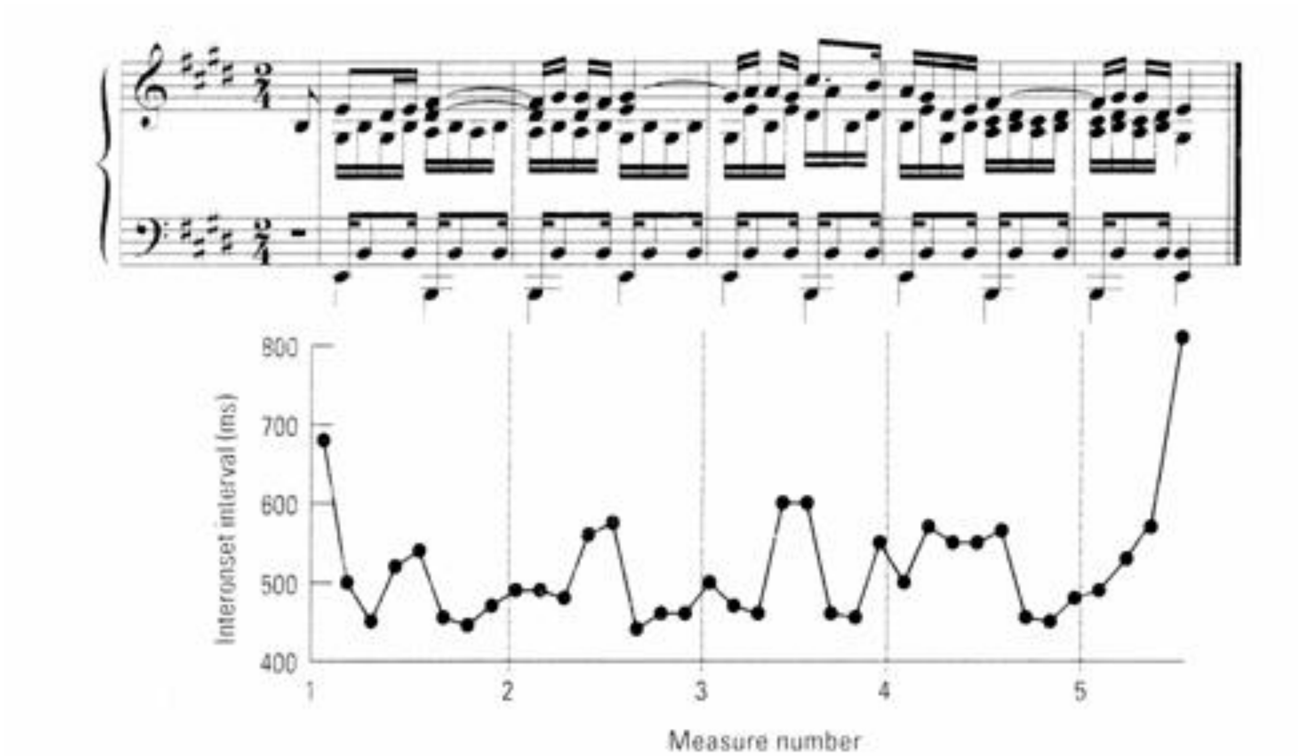




This example and the analysis is from Clayton (2000). Here the beats (matrā) are isochronous, but the metric level above the beat is not (an alternating pattern of 2 and then 3 beats in a 10 beat cycle). These 2 and 3 beat vibhāgs are difficult to hear if one is unaccustomed to counting the tāl, but are readily apparent to a North Indian listener from the characteristic Thēka, or drum pattern employed here.

To be sure, by definition the highest level of a repeating pattern is always isochronous, and most other levels of rhythmic structure tend to be isochronous. But Western music theory, from the 19th century through Lerdahl and Jackendoff (1983) has presumed meter to be inherently isochronous. Thus rhythms comprised of uneven beats and higher-order prime numbers of pulses (found in musical cultures ranging from Eastern Europe to Southern India) cannot be accommodated in western music theory.

Moreover, in western musical practice (as opposed to western musical notation), most rhythms are not truly isochronous. For even while they may be notated in even values, these "nominally isochronous" rhythms are performed with subtle nuances of timing and dynamics. Even when asked to play mechanically performers cannot. These nuances of timing and dynamics are complex, but they are also structured and replicable(Gabrielsson 1993, Repp 1998a). Moreover, listeners expect patterns of expressive variation (Drake 1993, Repp 1998b 1999, Drake Penel & Bigand 2000). Repp's studies showed that where we expect a slight lengthening we are more sensitive to shortening than additional lengthening, and (mutatis mutandis), where we expect a slight shortening, we are more sensitive to lengthening than extra shortening. Repp has also extensively studied the use of rubato in Chopin's piano music:



Here the graph below the score shows he duration of each IOI in milliseconds. As can be seen the note durations range from about 450ms to over 600ms. But these variations in duration form a complex pattern, one that reinforces the pitch structure of the melody (and the overall gesture of the phrase). In many ways the non-isochrony in this passage is far more complex than that found in the non-Western examples given above.

Three points can be made regarding these non-isochronous examples.

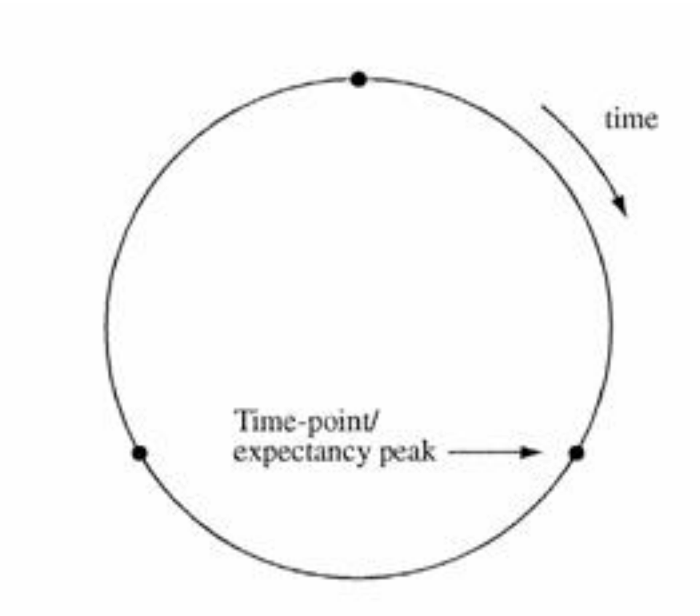
- The uneven beats in African and North Indian Rhythms are no more complex (no less regular) than the patterns of expressive timing that occur in western music. Indeed, in the case of performances with a high degree of rubato, the non-Western rhythms and meters may be considerably simpler.
- If the beat level itself is non-isochronous, then one cannot simply extrapolate a series of pulses (and/or higher levels) from a single IOI. Rather, one must grasp rhythmic patterns as temporal wholes. This suggests that listeners who are steeped in a particular musical culture will have a repertoire metrical

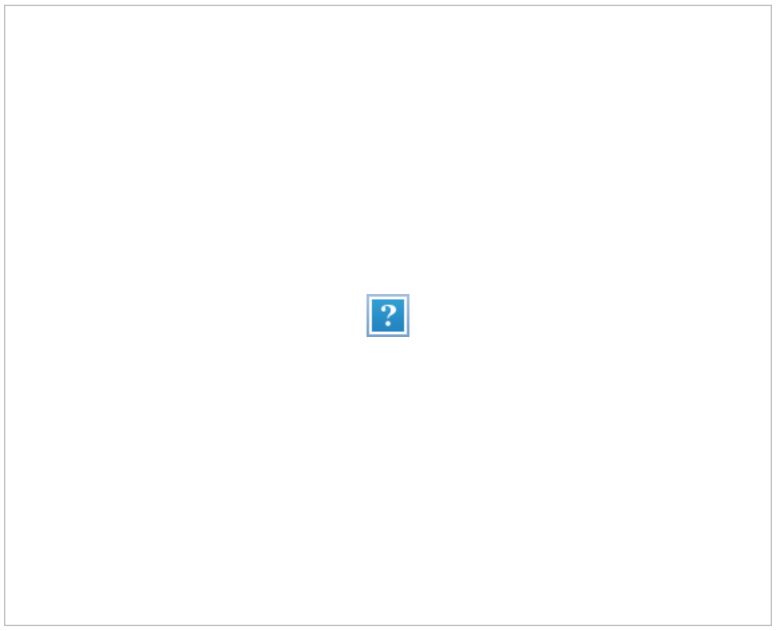
"templates" which allow them to readily grasp such patterns, both as the music starts and as it changes as it goes on.

- Given that as a general rule, one must grasp rhythmic patterns as "temporal gestalts," the distinction that is made between additive and multiplicative meter is specious. While there are systems of *notation* that may work additively (e.g., expressing a bell pattern as 2+2+3+2+3) or multiplicatively (e.g., where 6/8 is understood as a "compound duple" measure consisting of two triplets), these orthographies are simply shorthands for more complex patterns of sound in time that occur in performance. Actual performance timings involve complex ratios that neither add nor multiply in any simple fashion.

5. Maximal Evenness: A Theory of Rhythmic Regularity

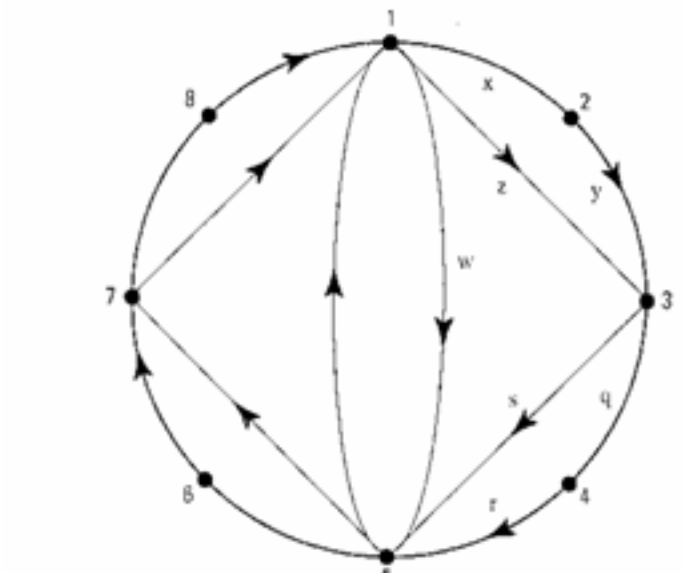
A metrical pattern—a pattern of entrainment—may be given a circular representation:





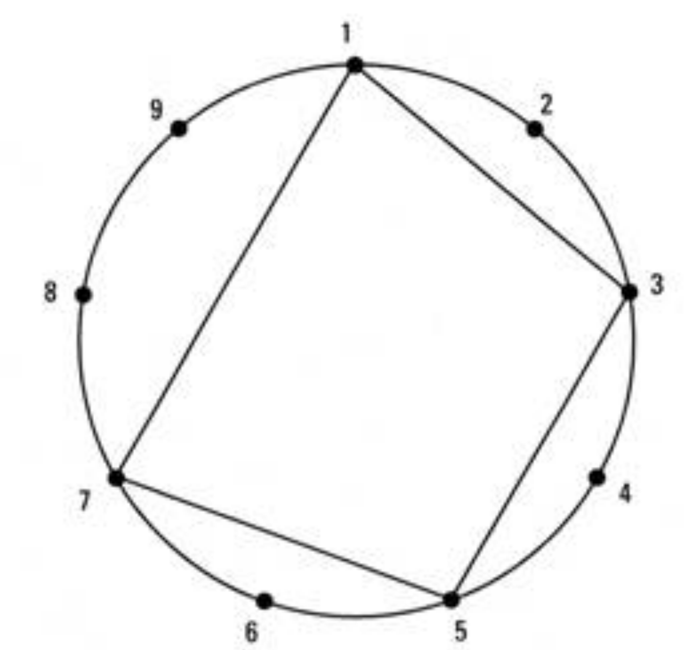
In this diagram, a simple three beat measure is represented as a circle with three equally-spaced points on its circumference. These points are peaks of attention, and may also be the temporal goal-points of action/motor behaviors (e.g., when a tapping figure hits a tabletop, or when a foot falls in a dance step). While these points may have been prompted by an external stimulus, the diagram represents the internal temporal timekeeping of the listener/tapper/dancer.

Both rhythms in the world and our metric responses to them are typically a bit more complex, involving several coordinated periodicities (what we would musically call levels of metrical structure). Here is another example:



As in the previous figure, the arrows represent the direction of temporal "flow." This is a typical measure of 4/4 time. The beats are mapped by the square figure that connects points 1, 3, 5, and 7. Subdivisions are marked on the rim of the circle. The oval figure that connections points 1 and 5 represents a half-note/half-measure level of entrainment.

In the 4/4 diagram, each and every periodicity is isochronous. Here is a different meter, one with a non-isochronous beat pattern:

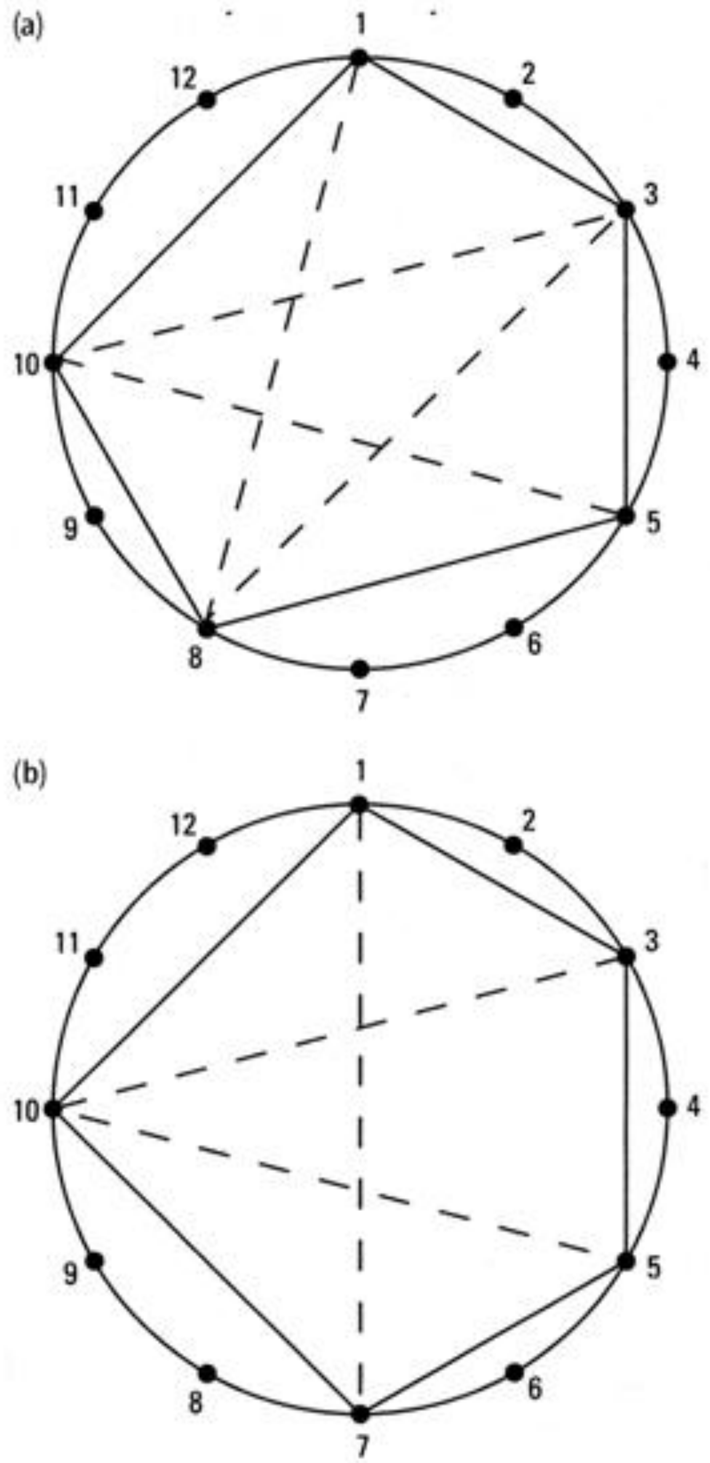


To hear a musical example of this, click HERE (opening measures of Dave Brubeck's "Blue Rondo al a Turk").

Like the previous diagram, we have a four beat measure. And this seems "regular enough." Why? The answer is that this pattern is *maximally even*. The notion of maximal evenness comes from group theory in mathematics, and has been used to account for well-formedness in musical scales (see Agmon 1996 and Clough and Douthett 1991). In group-theory terms, maximal evenness means simply that when dividing up a larger group into smaller sub groups, do so as "evenly as possible"—that is, without remainder (if possible), and if there is a remainder, then it should be distributed throughout as many of the subgroups as possible. In metrical terms, it means that the beats should be as evenly spaced as possible relative to a cycle of underlying subdivisions. Our circular representation of metrical patterns makes this easy to see. If the outer circle involves 9 elements, the best one can do in constructing a four beat meter is a 2+2+2+3 pattern, for 4 of course doesn't divide into 9 without a remainder.

Isochronous patterns are maximally even by definition, as the number of beats in a measure is always a whole-number factor of the total number of subdivisions. If the rhythmic tradition of a musical culture only involves isochronous meters, than considerations of maximal evenness, though present, never come to the forefront of our metric considerations; it simply isn't an issue. Non-isochronous meters, however, force us to consider the limits of rhythmic and metric regularity in a way that isochronous meters do not.

Maximal evenness: also makes clear the necessity of approaching meter, holistically (in terms of the organization of the entire metric pattern, and not just of any given level). Consider the bell pattern given on the audio excerpt above; it is pattern (a) below:



In pattern (a) the 5 beats are arranged over the cycle of 12 subdivisions in a 2+2+3+2+3 pattern. For 5 divides into 12 twice, with a remainder of two. In figure (a) the remainder is also spread out as evenly as possible—that is, it is not all lumped in one long beat (resulting in a 2+2+2+2+4, for reasons that should be obvious), and (b) the remainder is not put into two consecutive beats, yielding a 2+2+2+3+3 pattern. In pattern (a), the beats are "as evenly spaced as possible," and note how this approximates the arrangement one would find if there were five isochronous beats (whether they were 2+2+2+2+2 or 3+3+3+3+3) in terms of their deviation from perfect symmetry.

But look further at pattern (b). As the dashed lines show, the (2+2+2)+(3+3) pattern can be neatly be divided in half, while the dashed lines in pattern (a) show that it cannot. The best one can do with pattern (a) is a (5+7) arrangement of non-isochronous half measures (this is an example Simha Arom's "principle of rhythmic oddity). On the beat level, pattern (b) isn't maximally even, as the short beats are all clumped together. But the half-measure is maximally even. Thus maximal evenness is not an all-or-nothing affair; as metric complexity increases, so too does the manifestation of maximal evenness. Thus one cannot say that the 2+2+3+2+3 pattern is "more even" than the 2+2+2+3+3 pattern. Indeed, if the cycle of subdivisions is comprised of an odd number of elements, and/or if the beat cycle is non-isochronous, then one will have to steer a compromise between maximal evenness on the beat versus half-measure levels.

6. Conclusion

I hope this brief demonstration has convinced you of the relevance of both psychology and cross-cultural study to the study of musical meter. Of course, such an approach is not without its pitfalls. So in conclusion, let me acknowledge a few of the problems and shortcomings that remain:

My claims about the nature of metric entrainment and beat perception are based on empirical research. New data regarding our perceptual and cognitive capacities may (and probably will) lead to changes in the theory. This is especially true as we get more "ecologically valid" knowledge of our metric constraints and behaviors. For example, research that Bruno Repp, Peter Keller and I have recently carried out shows that the speed limits for beats and subdivision limits are context dependent, as one the subdivisions in non-isochronous meters need to be a good deal slower.

Maximal evenness as defined above presumes that a level of even subdivision is at least implicitly present in the music. But this is not always the case. In western music it is not uncommon for a few triplets to be interpolated in a context of otherwise duplet subdivision. Even more challenging is the Norwegian Springar rhythm. Springar involve 3 different beats (a long, a medium, and short) but no continuous subdivision, though there is lots of complex melodic ornamentation (Loberg Code 2005, Kvifte 2004).

The metric representations given above are "snapshots" of a particular attentional state, but meter is a dynamic and constantly-evolving aspect of our engagement with musical time. Thus a fully developed theory of meter-as-entrainment will need to model tempo changes, as well as the addition and/or subtraction of metric layers that occurs in real-time listening.

Finally, at different temporal levels, we characteristically have different kinds of motor behavior, different kinds of attention, different kinds of memory, and so forth. In a non-musical sense, different levels of rhythmic structure are connected to different kinds of events in the world. But when we play or listen to music, however, musicians (and especially music theorists) often presume that we integrates all these different processes into a single, coherent temporal framework. Likewise, our system of western metric notation does a beautiful job of encompassing many levels of rhythmic structure, from very rapid demi-semiquavers to entire phrases (marked with slurs and breath marks). But just because we can talk about "the meter" of a passage (in the singular), should we? Perhaps a better approach would be to have a more modular theory of meter: a theory of subdivision, a theory of beats, and so forth. While not as neat and tidy as a theory governed by a single set of metric well-formedness or preference rules, it may nonetheless be a better way to talk about musical meter.

BIBLIOGRAPHY

Agmon, Eytan. “Coherent Tone Systems: A Study in the Theory of Diatonicism.” *Journal of Music Theory* 40.1 (1996): 39-59.

Arom, Simha. *African Polyphony and Polyrhythm*. Cambridge University Press 1991.

Bilmes, Jeffrey Adam. "Timing Is of the Essence: Perceptual and Computational Techniques for Representing, Learning, and Reproducing Expressive Timing in Percussive Rhythm." Masters, MIT, 1993.

Bolton, T. L. "Rhythm." *American Journal of Psychology* 6 (1894): 145-238.

Brailoiu, Constantin. "Aksak Rhythm." In *Problems of Ethnomusicology*, edited by A. L. Lloyd (translator), 133-67. Cambridge: Cambridge University Press, 1984.

Clayton, Martin. *Time in Indian Music: Rhythm, Metre, and Form in North Indian Rag Performance*. New York: Oxford University Press, 2000.

Clough, John, and Jack Douthett. “Maximally Even Sets.” *Journal of Music Theory* 35.1&2 (1991): 93-173.

Drake, Carolyn. "Perceptual and Performed Accents in Musical Sequences." *Bulletin of the Psychonomic Society* 31, no. 2 (1993): 107-10.

Drake, Carolyn, Amandine Penel, and Emmanuel Bigand. "Tapping in Time with Mechanically and Expressively Performed Music." *Music Perception* 18, no. 1 (2000): 1-23.

Friberg, Anders, and Andreas Sundström. "Jazz Drummers' Swing Ration and Its Relation to the Soloist." Paper presented at the Bi-Annual Meeting of the Society for Music Perception and Cognition, Evanston, IL 1999.

Gabrielsson, Alf. "The Complexities of Rhythm." In *Psychology and Music: The Understanding of Melody and Rhythm*, edited by Thomas J. Tighe and W. Jay Dowling, 93-120. Hillsdale: Lawrence Erlbaum, 1993.

Glass, Leon, and Michael C. Mackey. *From Clocks to Chaos*. Princeton: Princeton University Press, 1988.

Hauptmann, Moritz. *Die Natur Der Harmonik Und Der Metrik Sur Theorie Der Musik (1853)*. Translated by W. E Heathcote. 1881 Edition, New York: Novello, Ewer, & co. ed. Leipzig: Breitkopf und Härtel, 1881.

Hirsh, Ira J. "Auditory Perception of Temporal Order." *Journal of the Acoustical Society of America* 31, no. 6 (1959): 759-67.

Hirsh, Ira J., Caroline B. Monohan, Ken W. Grant, and Punita G. Singh. "Studies in Auditory Timing: 1. Simple Patterns." *Perception and Psychophysics* 47, no. 3 (1990): 215-26.

James, William. *The Principles of Psychology*. two vols. Vol. One. New York: Dover Reprint, 1890, 1950.

Kvifte, Tellef. "Description of Grooves and Syntax/Process Dialectics." *Studia Musicologica Norvegica* 30 (2004): 54-77.

Lerdahl, Fred, and Ray Jackendoff. *A Generative Theory of Tonal Music*. Cambridge: MIT Press, 1983.

Lester, Joel. *The Rhythms of Tonal Music*. Carbondale: Southern Illinois University Press, 1986.

London, Justin. *Hearing in Time*. New York: Oxford University Press, 2004.

———. "Some Examples of Complex Meters and Their Implications for Models of Metric Perception." *Music Perception* 13, no. 1 (1995): 59-78.

Lussy, Mathis. *Traité De L'expression Musicale*. 3rd ed. Paris: Heugel & co., 1877.

Nketia, J. H. Kwabena. *African Music in Ghana*: Northwestern University Press, 1963.

———. *The Music of Africa*. New York: W.W. Norton, 1974.

Parncutt, Richard. "A Perceptual Model of Pulse Salience and Metrical Accent in Musical Rhythms." *Music Perception* 11, no. 4 (1994): 409-64.

Repp, Bruno H. "Rate Limits in Sensorimotor Synchronization with Auditory and Visual Sequences: The Synchronization Threshold and the Benefits and Costs of Interval Subdivision." *Journal of Motor Behavior* 35, no. 4 (2003): 355-70.

———. "Detecting Deviations from Metronomic Timing in Music: Effects of Perceptual Structure on the Mental Timekeeper." *Perception and Psychophysics* 61, no. 3 (1999): 529-48.

———. "A Microcosm of Musical Expression. I. Quantitative Analysis of Pianists' Timing in the Initial Measures of Chopin's Etude in E Major." *Journal of the Acoustical Society of America* 104, no. 2 (1998): 1085-100.

———. "Obligatory "Expectations" of Expressive Timing Induced by Perception of Musical Structure." *Psychological Research* 61 (1998): 33-43.

Repp, Bruno H., Justin London, and Peter Keller. ""Production and Synchronization of Uneven Rhythms at Fast Tempi" *Music Perception* 23, no.1 (2005): 61-78.

Riemann, Hugo. *Musikalische Dynamik Und Agogik: Lehrbuch Der Musikalischern Phrasierung*. Hamburg, 1884.

Sachs, Curt. *Rhythm and Tempo*. New York: Norton, 1953.

Woodrow, Herbert. "The Effect of Rate of Sequence Upon the Accuracy of Syncrhonization." *Journal of Experimental Psychology* 15, no. 4 (1932): 357-79.

Wundt, Wilhelm. *Grundzüge Der Physiologischen Psychologie*. Leipzig: Wilhelm Engelmann, 1911.