ANNUAL REVIEWS

The Psychology of Music: Rhythm and Movement

Daniel J. Levitin,[1] Jessica A. Grahn,[2] and Justin London[3]

[1]Department of Psychology, McGill University, Montreal, QC H3A 1G1, Canada;
email: daniel.levitin@mcgill.ca

[2]Department of Psychology and Brain and Mind Institute, Western University, London,
Ontario N6A 5B7, Canada; email: jgrahn@uwo.ca

[3]Departments of Music and Cognitive Science, Carleton College, Northfield, Minnesota 55057;
email: jlondon@carleton.edu

ANNUAL REVIEWS Further

Click here to view this article's online features:

- Download figures as PPT slides
- Navigate linked references
- Download citations
- Explore related articles
- Search keywords

Keywords

music perception, tempo, timing, rhythm, entrainment, movement

Abstract

The urge to move to music is universal among humans. Unlike visual art, which is manifest across space, music is manifest across time. When listeners get carried away by the music, either through movement (such as dancing) or through reverie (such as trance), it is usually the temporal qualities of the music—its pulse, tempo, and rhythmic patterns—that put them in this state. In this article, we review studies addressing rhythm, meter, movement, synchronization, entrainment, the perception of groove, and other temporal factors that constitute a first step to understanding how and why music literally moves us. The experiments we review span a range of methodological techniques, including neuroimaging, psychophysics, and traditional behavioral experiments, and we also summarize the current studies of animal synchronization, engaging an evolutionary perspective on human rhythmic perception and cognition.

Contents

1. INTRODUCTION

The field of music cognition traces its origins to the fourth century BCE, 2,000 years before the establishment of experimental psychology itself. Aristoxenus, an Aristotelian philosopher, went against the Pythagoreans, arguing that musical intervals should be classified by their effects on listeners, rather than merely examined in terms of their mathematical ratios (Griffiths et al. 2004, Levitin 1999). This argument focused the scientific study of music on the brain, followed (20 centuries later) by the first psychophysics experiments, which sought to map changes in the physical world onto changes in the psychological (mental) world [e.g., von Helmholtz 1954 (1863), Fechner 1860]. Many of the earliest studies in experimental psychology dealt with music, and the Gestalt psychology movement was formed to address questions about part–whole relationships in music and melody [von Ehrenfels 1988 (1890)].

Music has been defined as sound organized across time [Varèse & Wen-Chung 1966, Cage 2011 (1961)]. One of the most common human responses to music is to move to it, and many languages do not have separate words for music and dance (Besson & Schön 2001, Thompson 2014). Synchronizing our movements to music appears to be important for both listening and

performing (Cross 2005). We focus in this review on studies of music psychology that address rhythm, movement, synchronization, and temporal factors.

2. TEMPO AND TEMPORAL STRUCTURE

2.1. Definitions: Rhythm, Meter, Tactus, and Tempo

Rhythm is "the serial pattern of variable note durations in a melody" (Schulkind 1999, p. 896). Consider the song "Happy Birthday"—you can probably imagine the song in your head. Now tap out the rhythm: long-short-long-long-long-looong (pause); long-short-long-long-long-looong (pause). Rhythm consists of the relative durations of tones (or, more precisely, the relative timing of the intervals between note onsets). If you speed up or slow down Happy Birthday, the relative rhythmic proportions remain the same—the long notes are still longer than the short ones and by the same percentage.

At the same time that you hear the rhythm of Happy Birthday, you also feel a sense of pulse or beat, and, moreover, you hear those pulses in recurring groups of three (with implied rests before the singing begins):

```
(rest) (rest) Hap-py |birth day to |you, (rest) Hap-py |birth day to |you
  1      2     3      1    2   3    1     2     3     1    2   3    1.
```

This recurring pattern of pulses or beats defines the meter, the timing framework under which a given pattern of rhythmic durations is understood (as discussed in Section 2.4.1, meter entails entrainment). Meter organizes the perceived series of beats into regularly repeating patterns of stressed and unstressed beats; a musician would say that Happy Birthday is in 3/4 or waltz time, indicating that every third beat is stressed, starting with the first one, indicated by boldface type above. The rhythm–meter distinction is fundamental to a proper understanding of the psychology of rhythm and movement (McAuley 2010, London 2012).

Tactus refers to the most natural rate at which a listener might tap or clap their hands to a musical piece and is generally synonymous with the beat. However, individuals may disagree about the rate of the tactus (Martens 2011) because they extract different perceptual groupings from the musical signal—for example, some listeners may feel the beat at twice the rate of others in the same music (and thus clap their hands twice as often as others). Beat perception is typically strongest for tempos of approximately 100–120 beats per minute; this is believed to be related to a general shift from beat-based to interval processing at slow tempi in striato-thalamo-cortical networks (McAuley et al. 2012). This shift may be evolutionarily related to synchronized running behaviors among groups of early humans.

Tempo refers to the pace of music, or the rate at which musical events unfold over time (McAuley 2010). Although tempo is most strongly associated with beat rate [i.e., beats per minute (bpm)], multiple factors influence the perception of tempo, including event density, register, and loudness (Drake et al. 1999, London 2011). Musical tempos generally range from 40 to 200 bpm. As points of reference, Chopin's Funeral March (Chopin 1839, movement 3) is typically performed at approximately 48 bpm, Adele's "Hello" (Adkins & Kurstin 2015) is at 79 bpm, Michael Jackson's "Beat It" (Jackson 1983) is at 132 bpm, and Charlie Parker's "Bird Gets the Worm" (Parker 1949) is at 340 bpm.

Tempo plays a role in emotional interpretation. Generally speaking across cultures, slower tempos are associated with sadness or reflection, and faster tempos are associated with activity and happiness. Even 5-year-olds can make these associations (Poon & Schutz 2015, Swaminathan & Schellenberg 2015). Musical events span a timeline that runs from less than a millisecond in the
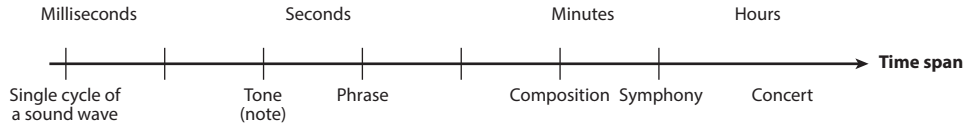
Musical events and time

Figure 1

Timeline of typical durations for different musical events.

case of a single cycle of a high-pitched sound wave, to 2–3 seconds in the case of the duration of a tone, to minutes or hours in the case of the duration of a composition (see **Figure 1**) (Levitin et al. 2002). However, when we discuss musical rhythm, we are most concerned with our perception of and interaction with sounds and sound patterns in the range of 100 ms to 5–6 s.

2.2. Discrimination

The just noticeable difference (JND) is the smallest discriminable change in a stimulus. Temporal JNDs can be expressed in terms of absolute durations or as tempo. Extradurational factors, particularly pitch and loudness, affect temporal JNDs (Jeon & Fricke 1997, Scharf & Buus 1986). For example, a 200 Hz tone must be presented for longer than a 1,000 Hz tone for the two to be considered equivalent durations (Burghardt 1973).

JNDs for musical duration have been shown to follow a modified version of Weber's law: The JND is approximately 2.5% for note lengths between 240 and 1,000 ms but becomes constant, rather than proportional, at 5–6 ms for note lengths below 240 ms (Abel 1972, Friberg & Sundberg 1995). For absolute duration of individual tones, JNDs as low as 10 ms have been reported (Friberg & Sundströöm 2002).

The JND for tempo discrimination varies according to the measurement method. In a listening task in which participants judged which of two tone sequences was faster, the JND was found to be 6.2–8.8% (Drake & Botte 1993, Miller & McAuley 2005). Using the psychophysical method of adjustment (the listener adjusts the difference between two stimuli until they are perceived to be equal), the JND was 4.5% (Friberg & Sundberg 1993). When participants judged the displacement of a single element in a continuous sequence, the JND for tempo was found to be approximately 6% (Hibi 1983). In discrimination of a swing rhythm from a march rhythm, JNDs as high as 20% have been reported (Friberg & Sundströöm 2002).

In related work on timing discrimination using actual musical performances, listeners rated performances of Chopin piano pieces that varied in timing and amplitude variability from 0% (deadpan) to 175% of normal performance values. The 100% version was more expressive than, for example, the 75% version, but less expressive than the 125% version, creating a natural ranking of expressivity in the excerpts presented. Participants effectively recreated the rank ordering of versions from most to least expressive, even though excerpts were presented at random and listeners were blind as to the manipulation. Listeners also rated how much they liked the different versions and showed a peak preference in the 100–120% range. Taken together, these findings suggest that there exists an optimal amount of timing and amplitude variability and that performers typically create within that range without prompting (Bhatara et al. 2011). Previously unreported in that research is the fact that the timing information that listeners based their judgments on was an average note length deviation of 68 ms (14%) and note onset variation of 153 ms (30%), representing a kind of temporal JND using real-world, ecologically valid stimuli.

In synchronization–continuation tasks, participants tap along with a pulse at a certain tempo (synchronization) or continue tapping at that tempo after the stimulus stops (continuation). By introducing perturbations (i.e., early or late stimulus onsets), researchers can measure the difference that is required for participants to notice and adjust their tapping to account for the error and stay synchronized. Corrections to differences of 3–4% have been reported for synchronization (Collyer et al. 1994, Povel 1981) and 7–11% for continuation (Allen 1975). Even better sensitivity, of 1–2%, is evident in the subliminal corrections we are able to make in maintaining synchrony with perturbed sequences (Repp 2000). As Repp has noted,

> . . . the temporal information available to the timekeeping and feedback mechanisms in sensorimotor coordination is different from the one that enables a listener to explicitly detect deviations from temporal regularity or judge the temporal order of two events. There appears to be a level of highly accurate temporal perception subserving motor control which precedes the level of conscious perception and judgment. (Repp 2000, p. 139)

This observation is consistent with the literature on judgements of cross-modal synchrony, which concludes that temporal order judgements ("Which came first?") are served by separate neural mechanisms than judgements of simultaneity ("Did they occur at the same time?"), with thresholds that differ accordingly (Cohen 1954, Hirsh & Sherrick 1961, Mitrani et al. 1986).

2.3. Memory

Memory for tempo has been shown to be robust and precise. This forms a parallel in the time domain to absolute pitch memory (Levitin & Rogers 2005). When nonmusicians sang their favorite popular songs from memory, their productions tended to occur within 4% of the JND for the original tempo (Levitin & Cook 1996), a finding that has been extended to labeling tempo markings (Gratton et al. 2016). Absolute tempo has also been found in mothers' production of songs for their infants (Bergeson & Trehub 2002). It is well known that professional drummers remember tempos with high accuracy, although this has not been studied experimentally. In contrast, changing the tempo of an unfamiliar musical piece has been shown to impair subsequent recognition (Halpern & Müllensiefen 2008), as the tempo appears to be encoded as an integral part of the song's identity, at least upon first hearing.

People can generally recognize familiar melodies when they fall within a range of 0.8 to 6 notes per second, but when they are sped up or slowed down beyond this range, recognition degrades considerably (Halpern & Andrews 2008, Warren et al. 1991). There are some styles of minimalist music, however, that involve very long, sustained durations, perhaps the most extreme example being John Cage's 1987 composition "Organ/ASLSP (As Slow as Possible)," the performance of which has lasted from 20 min to nearly 15 h; a version currently underway is planned to last 639 years (Judkis 2011). A novel application of the idea was released by the singer Publio Delgado, who performed Bach's "Cello Suite No. 1" by singing two notes per day for nearly a year (**https://www.youtube.com/watch?v=r4rc92Uoj74**).

Memory for rhythm, as distinct from tempo, is also robust under certain circumstances. One recent study sought to discover if certain songs are widely identifiable based on rhythmic information alone, presumably as a function of their underlying compositional features (Rosch 1978). That is, some songs may have rhythms with high cue validity. Participants heard 30 familiar songs and had to name the songs without receiving a list of possible song names. Three songs, when presented as click trains that therefore lacked pitch information, yielded uniformly high

identification rates: "Jingle Bells," Mendelssohn's "Wedding March," and "Deck the Halls" (Houlihan & Levitin 2011).

2.4. Beat Processing and Entrainment

The degree to which rhythms and beats induce corresponding movements falls along a continuum. Some rhythms (within a given musical culture or subculture) are easily ignored, whereas others can get an entire crowd on their feet. In 1989 America, the latter category might have included "Love Shack" by the B-52s, and in 2017, "You, I & the Music" by Junior Sanchez. Other pieces of music lead to unwanted movement: an audience taking to the exits, as happened at the premier of Igor Stravinsky's "Rite of Spring" and Bob Dylan's 1966 tour. In this section, we look at what is currently known about how musical beats are processed and how movement and auditory perception are linked. We revisit this topic in Section 6.

2.4.1. Entrainment and musical meter. Entrainment occurs when our bodily movements lock in to and synchronize with music. This process can be manifest as handclapping, playing a musical instrument, or dancing, for example. A self-sustaining oscillatory process in the brain becomes phase locked to the periodic input or stimulus (Glass & Mackey 1988). With music as the input, our internal neural firings and body movements are said to be driven by the external musical cues, especially those related to our sensorimotor system. These internal rhythmic processes are usually characterized as hierarchical oscillators tuned to particular temporal frequencies. Humans can entrain their movements to regular stimuli with almost perfect tempo matching (movement rate matching the beat rate) and phase matching (movements occurring at the beat onset time) (Repp & Su 2013). To achieve entrainment, an internal representation of the beat must exist, so that the individual can initiate their movements in synchrony with the beat rather than reacting to each beat (as would happen if the individual had to wait to hear the beat before initiating the movement). These processes are believed to be governed by a network that includes the cerebellum, the supplementary motor area (SMA), and the premotor cortex (PMC), as neurons fire in synchrony with the music (Cameron & Grahn 2014, Chen et al. 2006), with the temporal anticipation additionally involving Brodmann Area (BA) 47 (Levitin & Menon 2003).

Some of the earliest studies of entrainment measured the accuracy and variability of tapping to an auditory or visual sequence of events. Musical training can reduce the variability of tapping from approximately 4% down to 0.5–2% of the intertap interval. Taps tend to precede the target sequence tones by a few tens of milliseconds, rather than being distributed evenly before and after the tone onsets. This negative mean asynchrony is an indication that the regularity of the tone sequence has been perceived and that individuals are anticipating the timing of future tones. Although some studies have suggested a shift from anticipatory to reactive tapping as sequences slow down (the transition occurring at approximately 26 bpm; Mates et al. 1994), more comprehensive studies do not find any evidence for this shift, even when the interval between tone onsets is as long as 3.5 s (Repp & Doggett 2007).

Current models of rhythmic entrainment (Eck 2002, Large & Kolen 1994, Large & Palmer 2002, Toiviainen & Snyder 2003) posit that multiple internal oscillators phase lock to periodicities in a rhythm—most often to the beat, or tactus, but also to other levels of the metric hierarchy, such as the downbeats of successive measures. This phase locking is what allows a musician to keep track of multiple musical events simultaneously and to recover from errors while staying in time. The hierarchical oscillators are even more important for musicians who want to play rubato or before or behind the beat—they need to know exactly when various levels of beat are being experienced (by themselves, by listeners, and by other ensemble players) in order to expressively alter their own timing. Musicians often use these techniques. Frank Sinatra famously sang behind

the beat (giving the performance a cool quality), and Kendrick Lamar tends to sing ahead of the beat (giving the performance urgency).

Oscillator models reproduce features of human perception: They can resonate at frequencies that are not present in the input but that humans perceive (Large 2008, Large et al. 2010), allowing one to fill in missing beats or perceive loud rests (London 1993). When The Rascals stop playing completely during "Good Lovin'" and then start up again after a silent gap, we hear a loud rest and anticipate the re-entrance (Clark & Resnick 1966).

2.4.2. Rhythmic entrainment in the brain. An important component of beat perception is the perception of accents, by which certain events in a rhythmic sequence are perceived as more salient than others. Accents often emphasize the beat periodicity itself or certain beats relative to others. Syncopation (defined below) can create a sense of accent; for example, Herbie Hancock's song "Chameleon" (Hancock 1973) has a characteristic six-note riff that begins with three short pickup notes, and then the following three notes are on the beat, off the beat, and off the beat, creating a double syncopation.

Some accents are acoustically marked (e.g., by differences in the intensity of a tone), whereas others arise from top-down intentions or the expectations of the listener. For example, even in isochronous sequences (i.e., sequences in which the duration of every note is the same), and with tones that do not vary in pitch, listeners may spontaneously perceive some tones (e.g., every second or every third tone) as accented (Brochard et al. 2003).

The perception of accents relates to changes in oscillatory power in the delta band (1–4 Hz, which is the range for beat and meter perception) as well as in the beta band (15–30 Hz). For example, listening to an isochronous rhythm that has alternating accented and unaccented tones leads to increases in beta power on the accented tones (Iversen et al. 2009). Even simply imagining an accent on every second or third tone (that is, imposing a march or waltz meter on the perception of unaccented tones) enhances oscillatory power at the frequency of the imagined meter (Nozaradan et al. 2011, 2012). Imagined accents also alter oscillations in the beta frequency band, with greater beta power being measured for tones that are imagined to be accented than for those imagined to be unaccented (Iversen et al. 2009, Fujioka et al. 2015). More broadly, beta oscillations have been linked to movement and motor brain areas (Salmelin & Hari 1994), and their modulation during rhythm and beat perception provides evidence for the link between rhythm and the motor system. A causal link, however, between oscillatory power and beat perception remains to be conclusively demonstrated (Henry et al. 2017).

A key part of entrainment to the beat involves accurate prediction of upcoming events. Imagined or implied accents are a staple of composition in which the composer sets up an expectation for where the beat is but contradicts that expectation with the introduction of other instruments. Two contemporary examples are the songs "Hypnotized" (Welch 1973) and "Bodhisattva" (Becker & Fagen 1973): Both begin with a drum part that implies that the first tone sounded was on the downbeat (the one), but as other instruments are added, it becomes apparent that the drum pattern was, in fact, syncopated and did not start on the downbeat. More recent examples of this include Radiohead's (1997) "Paranoid Android" and Mbongwana Star's (2015) "Malukayi"; CSNY's "Woodstock" (Mitchell 1970) is a textbook example.

During beat perception and synchronization, sensory and motor brain areas are active. Functional magnetic resonance imaging (fMRI) studies have identified brain areas that are key for entrainment, including the basal ganglia (e.g., putamen), the SMA, and the PMC, as well as the auditory cortex and anterior insula (implicated in auditory memory) (Chen et al. 2008a,b, 2006; Grahn & Rowe 2009, 2012; Grahn & Brett 2007; Teki et al. 2011; Vuust et al. 2006). These motor areas are active in response to simply hearing a rhythm, even if no movement is made. The

basal ganglia and SMA appear to be particularly important for beat perception (Cameron et al. 2016, Grahn & Brett 2009), which alters communication within motor networks and between auditory and motor areas. During beat perception, greater connectivity is observed between the basal ganglia and cortical motor areas, such as the SMA and PMC (Grahn & Rowe 2009), as well as between the basal ganglia and auditory memory areas, such as the anterior insula (Kung et al. 2013). Finally, connectivity between the PMC and the auditory cortex increases as the salience of the beat in isochronous sequences increases (Chen et al. 2006).

2.4.3. Developmental research on entrainment. Synchronized movement to music emerges with no specific training and at a very young age. For example, in the first 2 years of life, and even prior to full control over their motor system (Martin 2005), infants move their bodies rhythmically in response to music (Zentner & Eerola 2010). Although these early movements are spontaneous and occur without any prompting, there is no evidence that they are accurately entrained to the beat. In some children, accurate entrainment ability emerges by age 3 or 4, but many children are not accurate until they are older (Eerola et al. 2006, McAuley et al. 2006). In addition, individuals vary in their preferred rates of entrainment, and these preferred rates (often measured with spontaneous tapping) change with age (Drake et al. 2000, McAuley et al. 2006). Younger children show a faster spontaneous tapping rate (approximately 400 ms; 150 bpm) than older children and adults (approximately 600 ms; 100 bpm), and young children are also more accurate when synchronizing with faster tempos. Although older children and adults have a slower preferred tempo, they are also more flexible and accurate and, thus, able to entrain well to both slow and fast tempos.

The perception of a regular beat in music has also been studied in newborns (Winkler et al. 2009) using the mismatch negativity (MMN). The MMN is a brain response reflecting cortical processing of rare, unexpected events in a series of ongoing standard events (Näätänen et al. 2007). It occurs rapidly after stimulus onset (and can occur even in response to stimuli that the participant is not paying attention to) and is characterized by a negative electrical component in an electroencephalogram (EEG). In adults, when notes that are on the beat, as opposed to off the beat, are omitted, the MMN is larger, suggesting that, in some cases, the beat is perceived preattentively. Similar results were found in newborn infants, although the stimuli in that study confounded beat changes with changes in the number of instruments sounding (Winkler et al. 2009).

Several studies have demonstrated a developmental link between rhythmic abilities and language. Children who are better able to entrain to a metronome also have better language skills, including phonological awareness and verbal memory (Carr et al. 2014, 2016). Reading skills in adults are also correlated with entrainment accuracy (Tierney & Kraus 2013), and both children and adults with reading disabilities often have difficulty entraining taps to a metronome (Thomson & Goswami 2008, Thomson et al. 2006). Tapping steadily in silence is less associated with language skills than entraining to an external metronome (Thomson & Goswami 2008, Thomson et al. 2006, Tierney & Kraus 2013), suggesting that the ability to integrate auditory input with motor output is a key factor in the relationship between rhythm and language.

2.5. Evolutionary Approaches: Entrainment in Nonhuman Species

Although beat perception was long thought to be unique to humans, investigations have recently turned to nonhuman animals (Cook et al. 2013, Patel et al. 2009, Schachner et al. 2009). Snowball, the dancing cockatiel and YouTube sensation (**https://www.youtube.com/watch?v=cJOZp2ZftCw**), can bob his head to music (Patel et al. 2009, Schachner et al. 2009), but when recorded and analyzed under controlled conditions, Snowball showed only brief periods of synchronization and only around a narrow range of tempos, and he performed better when he

could see his human handler. Humans, in contrast, can flexibly synchronize across a wide tempo range and without visual cues. There is also preliminary evidence that budgerigars, bonobos, chimpanzees, and elephants may be able to spontaneously synchronize to simple stimuli, such as metronome tones (Hasegawa et al. 2011, Hattori et al. 2013, Large & Gray 2015, Schachner et al. 2009). Currently, the best nonhuman example of complex entrainment is a California sea lion named Ronan. Ronan accurately bobs her head in synchrony with isochronous sequences as well as with music, and can generalize this ability in response to music she has never heard before (Cook et al. 2013, Rouse et al. 2016). Moreover, her behavior matches the predictions of oscillator models that display coupling between auditory and motor oscillators, suggesting Ronan's behavior is similar to that of humans (Rouse et al. 2016).

Entrainment behavior has been directly compared between human and nonhuman primates with synchronization–continuation tapping tasks (in which tapping is synchronized with an isochronous sequence and then continues at the same rate after the sequence stops). Rhesus macaques and humans are similarly accurate when reproducing single time intervals, but humans are far superior when synchronizing with metronome sequences (Zarco et al. 2009) and performing continuation tapping. Moreover, macaques tap 100–250 ms after stimulus onset, whereas humans tend to tap ahead of the beat, indicating that the macaques are not employing prediction processes.

EEG studies with macaques have shown that unexpected tone omissions from isochronous tone sequences elicit an MMN similar to that of humans. Unlike humans, however, macaques did not show different MMN responses for on- and off-beat omissions, suggesting that they are unable to detect the beat (or syncopation) in rhythm. Monkeys can extract temporal information from isochronous metronome sequences but not from more complex rhythms. In one study, macaques showed changes of gaze and facial expressions in response to deviations in isochronous but not irregular sequences, whereas humans accurately detected deviations in both types of sequences (Selezneva et al. 2013). Overall, these findings suggest that monkeys have some capabilities for beat perception, particularly when the stimuli are isochronous. Thus, macaques may possess some, but not all, of the brain machinery used in humans for beat perception and entrained movement (Merchant & Honing 2014, Patel & Iversen 2014). Crucial evolutionary changes in the human brain that allowed for music included mechanisms for extracting structure from an acoustic stream, mental representation, and prediction. A key region in humans for music, BA 44, is far less developed in macaques (Petrides & Pandya 2002). Moreover, the human brain has far more folds and convolutions than the macaque brain, making it possible to squeeze millions more neurons into a relatively confined space. These differences in fine structure (BA 44) and gross structure (folds) may be the reason why monkeys lack the musical abilities of humans.

Studies of nonhuman animals have led to two theories regarding the capacity for beat perception. One suggests that beat perception occurs only in species that are capable of vocal learning (the ability to alter vocalizations in response to environmental input), as supported by neural connections that link auditory input with vocal motor control (Patel 2006). Snowball, as a cockatiel, is a vocal learner, as are budgerigars (Patel et al. 2009). The second account suggests that timing abilities in primates correlate with greater anatomical connections between auditory and motor areas (Merchant & Honing 2014). Rhesus macaques have limited connections between auditory and motor areas and can perform only basic timing tasks such as producing single time intervals (Merchant et al. 2013), whereas chimpanzees—who developed roughly 13 million years later than macaques—have more connections and have shown some ability to spontaneously synchronize (Hattori et al. 2013). However, neither account explains the existence of beat perception in all of the nonhuman species (including animals that are neither primates nor vocal learners) that demonstrate it, such as sea lions like Ronan (Cook et al. 2013).

3. SYNCHRONIZATION

3.1. Tapping

Tapping studies have revealed much about auditory–motor entrainment. We distinguish two adaptive processes, one predictive, the other reactive. One way to test these processes is to introduce various perturbations to a sequence as participants tap along with it and observe how they adapt to the perturbation(s). Changing the timing of a single note creates a large tap-to-target asynchrony, which requires adjustment of the timing of the following tap (e.g., Repp 2002, Repp & Keller 2004). This reactive adjustment is automatic and is called the phase correction response (Repp 2005). Phase correction occurs even when the perturbation is not consciously detected (Repp 2005). Moreover, the kinematics of the tapping movement change as quickly as 100 ms after the perturbation (Hove et al. 2014), which is sufficiently fast to indicate that phase correction is likely subcortical.

In music, many expressive timing variations or alterations in tempo tend to occur globally and in largely predictable ways (Bhatara et al. 2011). Anticipatory processes are more important for remaining synchronized during these types of changes (van der Steen et al. 2015), and individuals are more able to remain synchronized when the changes are larger, perhaps because they are more perceptible.

3.2. Walking

Synchronization and its effects on movement have also been investigated with respect to walking (Leow et al. 2014, 2015; Leman et al. 2013; Styns et al. 2007). One question of interest is whether people spontaneously synchronize their footsteps to music. In both laboratory and naturalistic settings, people generally perform this synchronization only when they are specifically instructed to do so (Franěk et al. 2014, Mendonça et al. 2014). Thus, although spontaneous synchronization can occur during certain physical activities, it is not common during walking. This may be why, for thousands of years, groups of humans who march (such as military units) have made an effort to practice such synchronization (McNeill 1995).

People walk faster to music than to metronomes (Styns et al. 2007), and it is not simply the beat that drives movement. When individuals are asked to walk to a variety of music that has the same beat rate (130 bpm), some songs cause faster walking, but others cause slower walking (Leman et al. 2013). Thus, expressive factors in the music are important and can explain up to 60% of the variance in walking speed. Perceived groove and familiarity also increase walking speed (Leow et al. 2014, 2015), with the effects of groove being much larger than the effects of familiarity.

3.3. Dyads and Larger Groups

When groups of people synchronize their movements, such as during group music performance, the interactions between sound and movement can be highly complex. Group performance requires generation of an internal beat through the collectively produced auditory rhythms and the simultaneous individual tracking of that beat. Individual musicians must adjust the timing of their movements to the subtle errors and asynchronies among other musicians, as well as between other musicians and themselves, to maintain the ongoing, predictable temporal structure of music.

The ability to synchronize with others in dyadic tapping is related to individual differences in the ability to predictively track, or anticipate, a regular beat (Pecenka & Keller 2011). In addition, successful adjustment of timing requires adaptation to unexpected timing changes, and these

two skills—anticipation and adjustment—predict synchronization success independently and in interaction (Mills et al. 2015). In dyadic, synchronized tapping, individuals benefit from mutual adaptation, adjusting to one another's subtle deviations and corrections in real time to maintain stable synchronization and minimize asynchronies between taps (Himberg 2014, Konvalinka et al. 2010, Nowicki et al. 2013). Interestingly, humans engaging in dyadic tapping demonstrate greater synchronization than one human tapping with a regular, computer-generated rhythm (Himberg 2014). Interpersonal synchronization in larger groups requires more complex interactions. String quartets, for example, can display autocratic and democratic behaviors, when, respectively, "following" musicians adjust their timing in response to the "leader" (autocratic) versus when all musicians mutually adjust their timings (democratic; see Wing et al. 2014).

Music listening, as shown by fMRI, synchronizes brain responses across listeners in networks spanning a wide range of regions: the brain stem, the bilateral auditory midbrain and thalamus, the primary auditory and auditory association cortices, right-lateralized structures in the frontal and parietal cortices, and the PMC (Abrams et al. 2013). These effects are greater for natural music than for quasi-musical control stimuli. Remarkably, intersubject synchronization in the midbrain (inferior colliculus) and thalamus (medial geniculate nucleus) was also found to be greater for natural music. This indicates that synchronization at these early stages of auditory processing is not simply driven by spectro-temporal features of the stimulus, which are processed in higher cortical structures. Increased synchronization was also evident in a right-hemisphere frontoparietal attention network and bilateral cortical regions involved in motor planning.

4. EMBODIED COGNITION OF RHYTHM AND MOVEMENT

4.1. Metrical Embodiment

Spontaneous movement in adults is generally synchronized to the beat, but it is also influenced by metrical levels other than the beat (Burger et al. 2013). The movements selected during dancing, for example, differ depending on the metrical level that the movement is synchronized to. For example, arm movements from the body out to the side are at the beat rate or slower, whereas vertical hand and torso movements occur at the beat rate (Toiviainen et al. 2010). Rotation of the torso and swaying of the body from side to side occur at even slower rates (e.g., four times the beat rate). The movement rates may relate to the amount of energy expended to move, and, thus, we select slower rates for parts that require more energy (Toiviainen et al. 2010). Timbral features of music also affect movement (Burger et al. 2013). The length, overall size and stiffness of a limb also constrain the natural harmonic oscillation rate and variability for movement (Lametti & Ostry 2010). Head movements tend to be synchronized to low-frequency sounds (e.g., the kick drum or bass guitar in popular music and jazz), whereas hand movements tend to be synchronized to high-frequency sounds (e.g., hi-hat or cymbal), perhaps because the freedom of movement of the hands enables them to synchronize to the faster rates presented in the higher-frequency percussion sounds. Finally, when there is a clear, strong beat in the music, overall body movements tend to be more regular and stable in their timing; when the beat is weaker or less regular, body movements are also less temporally regular (Burger et al. 2013).

Movement to the beat can alter meter perception. In one study, babies were bounced to an ambiguous rhythm—one group was bounced every other beat, whereas another group was bounced every third beat. Babies in each group were subsequently biased in their recognition of a binary or ternary accented version of the rhythm, respectively, as familiar, even though they had only ever heard an ambiguous unaccented rhythm (Phillips-Silver & Trainor 2005). A neural correlate of this result has also been shown by EEG (Chemin et al. 2014). Participants listened to a rhythm

while an EEG was recorded; they then moved their body (e.g., nodding or clapping) in either a binary or ternary fashion to the rhythm, and the EEG was recorded after this movement (when participants were still). The oscillatory power at either binary or ternary frequencies was enhanced based on the way that they had previously moved to the rhythm. Thus, moving to rhythm alters subsequent perception of that rhythm, as well as neural entrainment.

4.2. Bodily Movement and Timing Sensitivity

Moving to the beat can influence beat perception and timing accuracy. Tapping along to auditory rhythms enhances beat finding for complex rhythms (Su & Pöppel 2012). Tapping may direct attention to the beat, improving the ability to detect it and synchronize to it. In another study, participants tapped in time with an isochronous sequence and then judged whether a final probe tone heard after the sequence stopped was on time (Manning & Schutz 2013). When people tapped during the initial sequence, they were more accurate than when they did not. Importantly, this did not depend on producing a tap along with the probe tone: Timing was better even when tapping ended before the probe tone, indicating that participants were not simply comparing the probe tone position with their final tap. When percussionists completed the task, moving along helped them even more than it did musical novices, although, interestingly, novices and percussionists performed similarly when just listening (Manning & Schutz 2016). Thus, engaging in movement appears to alter both beat perception and timing accuracy and produces greater benefits in those with extensive training.

Musicians and nonmusicians who tapped in synchrony with progressively more complex and less metrically structured auditory rhythms showed, in fMRI, a functionally connected network involving the dorsal PMC, possibly involved in extracting higher-order features of the rhythm's temporal structure (Chen et al. 2008b). Musicians recruited the prefrontal cortex to a greater degree than did nonmusicians, whereas secondary motor regions were recruited to the same extent. The superior ability of musicians to deconstruct and organize a rhythm's temporal structure may relate to the greater involvement of the prefrontal cortex in mediating working memory and may possibly involve the documented leftward shift as musical expertise increases (Bhattacharya & Petsche 2005, Kuchenbuch et al. 2012).

4.3. Rhythm Perception and Production and Theories of Embodied Cognition

The intimate relationship between music and movement has led researchers to examine how music perception is influenced by the physical properties of the human body, a process known as embodied music cognition (Leman & Maes 2015). Embodied cognition suggests that many higher cognitive functions are grounded in lower-level sensorimotor functioning. The reciprocal influence between movement and perception, as well as the activation of motor brain areas during rhythm perception (both detailed above), are often taken as indirect support for embodied music cognition. Leman & Maes propose that our acquired associations between motor output and the consequent sensory input creates an integrated network underlying both music production and music perception.

An additional line of evidence is the fact that we are able to distinguish who is producing actions based on sound alone (Sevdalis & Keller 2014). Even very simple auditory information, such as clapping or taps, can enable identification, and the tempo and variations in timing seem to be among the most important cues. This identification also occurs when expert music listeners identify, say, a favorite saxophone player based on subtle differences in parameters of timing and timbre. Allocating agency to an auditory action recruits mental simulations that relies on motor systems (Jeannerod 2006, Sevdalis & Keller 2014), and these systems are used to predict

the auditory properties of our own movements, as well as those of others. These findings are consistent with claims that music has an evolutionary basis in signaling and sharing information, including an individual's identity, among conspecifics.

5. RHYTHMIC PATHOLOGIES AS MOVEMENT DEFICITS

5.1. Beat Deafness

Beat perception is a universal human capacity, yet a few reported cases of beat deafness—a type of amusia—exist, in which individuals show severe limitations in their capacity to perceive and synchronize to a musical beat despite having no rhythmic deficits in other domains, such as motor coordination and speech (Levitin 1999, Phillips-Silver et al. 2011). One reported individual, Mathieu, could neither bounce up and down to the beat of music nor accurately judge whether a video of a dancer was synchronized with the perceived music (Phillips-Silver et al. 2011). Yet Mathieu was able to synchronize his bouncing with a metronome. Mathieu and another beat deaf individual, Marjorie, were also asked to synchronize tapping with a metronome that was occasionally perturbed. Although both showed some ability to readjust their tapping following a perturbation, they took abnormally long to do so compared to controls (Palmer et al. 2014). Moreover, their tapping performance was assessed using a harmonic oscillator model, which found that Mathieu and Marjorie had different underlying deficits (involving intrinsic oscillator frequency and relaxation time, respectively).

Heterogeneity in deficits of beat perception and synchronization was further suggested in a tapping study in which seven individuals out of a sample of 99 showed abnormally poor synchronization (Sowiński & Dalla Bella 2013). Two of the poor synchronizers met the criteria to be considered beat deaf (presenting deficits in beat perception and synchronization but not in pitch perception), and two others showed selective deficits in synchronizing to real music but normal sensitivity to changes in durations and rhythms.

5.2. Brain Lesions and Disorders

Damage to or dysfunction in motor brain areas can produce timing and rhythm problems that cannot be attributable solely to motor problems. One example is seen in Parkinson's disease, a neurological disorder that impairs basal ganglia function and movement. The ability of Parkinson's patients to perceive changes in rhythmic patterns is significantly impaired compared to healthy controls (Cameron et al. 2016, Grahn & Brett 2009), even though no movement is required for the task. Similarly, patients with other basal ganglia disorders, such as Huntington's disease or multiple system atrophy, show deficits on a battery of rhythm and timing tasks (Cope et al. 2014). Finally, when basal ganglia lesion patients are asked to synchronize to a sequence with gradual tempo changes, they show higher timing variability than controls (Schwartze et al. 2011, van der Steen 2015). Modeling of the variability suggests that internal timekeeping processes are noisy in these patients and that their ability to accurately predict tempo changes has been reduced.

6. GROOVE

6.1. Definition of Groove

It is one thing to be able to tap your toe along with a drumbeat or melody—it is something else when the music compels you to move along with it. This compulsion is the essence of groove

(also called pocket). Groove is defined as "the urge to move in response to music, combined with the positive affect associated with the coupling of sensory and motor processes while engaging with music" (Janata et al. 2012, p. 54). In jazz, groove is associated with the swing rhythm applied in performance, one in which a series of notes with the same notated duration are performed with a "forward propelling directionality" (Schuller 1968, p. 7). This is typically accomplished by dividing a beat unevenly, with the first subdivision about twice as long as the second. The sense of swing or groove is not experienced analytically, but rather through our bodily engagement with the music (Iyer 2002, Roholt 2014). In moving to groovy music, we become aware of its rhythmic flow, and groove is manifested as the kinematic feeling arising from one's embodied experience of entrainment to the music. Groove, then, is a pleasurable response to certain musical rhythms that not only compel us to move, but also make us aware of the way that our bodies are moving with the music.

What is it in the music that gives rise to a sense of groove? Madison (2006) presented listeners with music from a wide range of musical styles and genres, including music from Africa, India, Latin America, and Southern Europe. Listeners rated each example on a number of descriptive terms, including groove. Listeners were able to make ratings of amount of groove (grooviness) just as readily as other factors, and groove was associated with music that was also "driving, intensive, and somewhat rapid and bouncing" (Madison 2006, p. 206). Moreover, grooviness was associated with more than one musical style and genre, and it was consistently recognized (i.e., there was good intersubjective agreement as to what was groovy). Janata et al. (2012) had listeners rate the grooviness of a large sample of North American popular music. They found that, whereas R&B music (that is, Motown and Soul but not Hip-Hop or Rap), was rated higher for groove than were other genres (Rock, Folk, and Jazz), there were no significant differences among other genres, at least in their sample of university students. Faster music (>100 bpm) tended to be rated higher for groove than slower music, as was music that was familiar or enjoyed by participants. Janata et al. also had participants move in various ways, including (*a*) tapping along to an isochronous beat, (*b*) freely tapping in any rhythm along with the music, and (*c*) not tapping. Participants felt that it was easier to tap along with high- than with low-groove music and felt more in the groove with high-groove stimuli. Analysis of video data from the nontapping condition found that higher-groove music gave rise to spontaneous body movements (e.g., of the head, torso, or foot) to a significantly greater degree than did low-groove music. Music with high groove gives rise to robust sensorimotor entrainment, and groove strength is correlated with beat strength and pulse strength.

6.2. Groovy Structural Factors: Swing and Syncopation

What are the structural factors of the music that give rise to a sense of groove? Given that groove is correlated with a strong sense of felt beat, groove is sensitive to tempo, as is beat induction more generally (van Noorden & Moelants 1999); as noted above, groovy music tends to fall within a moderate to quick tempo range (100–130 bpm; Janata et al. 2012).

Various studies have examined two other structural factors: rhythmic complexity and expressive timing, or rather, swing. Both are thought to influence groove because the listener must make a greater effort to follow the rhythmic flow than would be the case with a simple and wholly predictable series of durations performed with a deadpan timing. The working hypothesis is that syncopations and expressive timing deviations optimize the listener's predictive engagement with the unfolding rhythm, making listening an active rather than passive activity. This was the basis of Keil's (1987) theory of participatory discrepancies in jazz, which was adopted by Iyer (2002), who posited that fine-grained timing variations are an essential aspect of groove. In many

styles associated with groove (e.g., jazz, R&B), rhythms are swung to varying degrees and, thus, systematically deviate from deadpan timing. Other studies have found that microtiming deviations were not required to give a sense of groove (Butterfield 2010, Fruhauf et al. 2013, Madison 2006, Senn et al. 2016), and in some cases, deadpan timings were preferred. These results make some sense, as Repp (2005) has noted that the phase corrections one makes in following fine-grained timing variations are often subliminal and involuntary, whereas only larger shifts in tempo (i.e., period corrections) involve conscious awareness and volitional control.

Empirical evidence for optimization of predictive engagement comes from studies of syncopation and groove. Defining syncopation is difficult, as it can manifest in different ways in different rhythmic contexts, depending on the number of beats in the measure and the ways in which the beats themselves are divided. Syncopation most typically occurs in 4-beat meters in which the beats are divided into eighth-note duplets. In this example, the integers represent the beats proper (the first eighth note of each duplet), and the word *and* represents the offbeat position (the second eighth note of each duplet): 1 *and* 2 *and* 3 *and* 4 *and* etc. A syncopation occurs when a note is articulated on one of the *ands* and is then held through the following eighth note. The characteristic bump one feels from syncopation occurs because the listener fills in the missing beat (see Huron 2006). Amounts of syncopation vary, but too much syncopation effaces the sense of beat, essentially creating an unsyncopated rhythm that has been phase shifted. Moderate amounts of syncopation result in the highest groove responses (Witek et al. 2014). In addition to syncopation, higher rhythmic density—more subdivisions of the beat—and rhythmic complexity also contribute to a sense of groove: Once a passage is composed with a certain amount of rhythmic density and syncopation, it is difficult to remove the sense of groove that results (Madison & Sioros 2014). This may explain why deadpan timings did not hurt the perceived groove of the stimuli used in previous experiments.

6.3. Groovy Listeners and Groovy Music

The operational definition of groove used in the studies given above—"the urge to move with the music and take pleasure in doing so" (Janata et al. 2012, p. 54)—is clearly dependent on the listener's receptiveness and mental and physical responses. Even music that was found to be highly rated for groove in some studies [e.g., Stevie Wonder's Superstition, which had the highest overall rating in the study by Janata et al. (2012)] may leave some listeners unmoved. An open question is how devotees of marches, folk dances, or historical dance styles would respond to music from these respective repertoires, as well as to contemporary music with high groove ratings in previous studies. Experts show greater sensitivity to changes in microtiming than do nonexperts (Bhatara et al. 2011, Senn et al. 2016). Complicating the scientific study of groove, participants sometimes report that a musical excerpt gives them the urge to move but do not move to it, and participants also sometimes move to music that did not give them a reported urge to move. "It seems that the groove experience is not that easy to measure. It will take considerable effort to develop reliable methods to assess a listeners' groove experience and bodily entrainment" (Senn et al. 2016, p. 12).

7. CROSS-MODAL CORRESPONDENCES IN RHYTHM PERCEPTION

7.1. Cross-Modal Correspondences: Perception, Integration, and Synesthesia

We usually think of rhythm as an auditory parameter arising from repetitive behaviors that create periodic sound patterns (as in, "He tapped out a staccato rhythm as he hammered the shingles on his roof"). However, rhythms can also be perceived via other sensory modalities, including our

haptic, proprioceptive, visual, and vestibular systems (Kosonen & Raisamo 2006, Phillips-Silver & Trainor 2008, Trainor et al. 2009). After audition, vision plays the greatest role in our temporal processes and perception of events in the world. The McGurk effect (McGurk & MacDonald 1976), in which the phonetic articulation we see influences what phonemes we hear, is just one of many examples of the influence of vision in auditory perception (e.g., Colavita 1974, Posner et al. 1976). Visual cues can alter musical experiences (Vines et al. 2011), and the influence of vision can change with age (Diaconescu et al. 2013).

Repeated elements in static images and sculptures may be described in terms of their visual rhythm, or an impression of coherence and movement created by pattern, repetition, and regularity in the arrangement of objects in the visual field. Although this is an important aspect of visual perception (as are the temporal aspects of vision, such as the saccades of the eye), in this section, we focus on the visual apprehension of dynamic processes and arrays and its relation to temporal perception in music. We distinguish among the following factors:

- cross-modal perception, in which perceptions in two modalities remain distinct but are mutually influencing;
- multisensory integration, in which sensations from two sensory modalities are fused into a single percept; and
- synesthesia, in which vivid percepts arise in one modality due to stimulation in another modality (Talsma et al. 2009). There are at least 35 types of documented synesthesia (Day 2005), including tone–color synesthesia, in which individuals report seeing colors in their visual field in response to hearing particular pitches. These tone–color associations do not appear to be systematic across individuals.

7.2. Rhythm and Motion in Vision and Audition

Perceiving a visual rhythm depends on either (*a*) a periodic change in the appearance of a stationary object, such as a flashing light or rotating multicolored ball, or (*b*) a periodic movement of an object, such as a bouncing ball or the steps of a dancer. It is also possible for an array of static objects, such as a series of flashing lights, to produce the illusion of motion. Such apparent motions depend on the sequential presentation of visual information, governed by the time and distance between successive events according to Korte's third law of apparent motion (Korte 1915, Shiffrar 2005). Although we hear a similar type of motion when we listen to music, this perception is also illusory, a kind of virtual motion in a virtual space of pitch or rhythm (Gjerdingen 1994, Langer 1953). Similar temporal constraints in neural processing appear to operate across the two sensory modalities.

Tests of our visual perception of rhythm have long used many of the same approaches and methods as those of auditory perception, replacing the clicks of a metronome or the sustained sine tones of a durational sequence with flashing lights. Initial experiments using these discrete visual stimuli indicated that vision seemed to be an order of magnitude slower and less accurate for tasks such as synchronization, durational discrimination, and perturbation detection (Grahn 2012, Grondin & McAuley 2009, Repp & Penel 2002). However, more recent studies using continuous visual stimuli, such as a bouncing ball, a light that continuously varies in intensity, or a rotating disc, found that, under these circumstances, differences between the two modalities largely disappeared (Grahn 2012, Hove et al. 2013, Iversen et al. 2015, Varlet et al. 2012), especially if the stimulus presented a physically realistic motion trajectory (Iversen et al. 2015). Moreover, when an individual tracks a periodically moving object, such as a conductor's baton, the absolute acceleration along the object's movement trajectory is the main cue for rhythmic periodicity and temporal location, although beat clarity and tempo are also important (Luck & Sloboda 2009).

Moreover, although one may associate discontinuous or discrete events with beat-based timing and continuous events with interval timing, continuously varying visual stimuli can also give rise to beat-based timing (Grahn 2012, Su & Salazar-López 2016). In addition, a beat may be perceived in visual stimuli when an individual is primed by hearing an auditory version of the rhythm before seeing it (Grahn et al. 2011).

Differences in temporal continuity across different modalities may inhibit perceptual integration, either because different neural systems are used to sense and encode discrete and continuous stimuli in each modality (a failure of structural correspondence) or simply because paired stimuli with continuity mismatches simply do not occur as part of our natural experience and, thus, give rise to a failure of statistical correspondence. Moreover, statistical correspondences are normally grounded in causal relationships that are understood to exist between auditory and visual stimuli, i.e., when one observes the action that gives rise to a sound (Schutz & Kubovy 2009). For example, one typically observes continuous motion, such as the movement of a violin bow, co-occurring with the production a continuous sound (the sustained violin tone). Similarly, discrete motions, such as the impact of a drumstick, co-occur with discontinuous sounds (a sharp, short drumbeat). Yet even this association is not consistent. Schutz & Lipscomb (2007) found that modifying the continuity of a visually presented marimba stroke—a short and jerky impact motion versus a longer sweeping impact motion—gave rise to illusory differences in the perceived tone duration (see also Varlet et al. 2012). Schutz & Kubovy (2009) further noted that the causal link between observed action and resultant sound could not be violated; when the impact motion (a marimba stroke) was paired with a different impact sound (a piano note), the illusion was weaker, and when it was paired with a nonimpact sound, the illusion did not occur. They took this to be support for the binding by causality hypothesis: There needs to be not only a statistical correspondence between what one sees and hears, but also a causal link when one is appropriate (Schutz & Kubovy 2009).

7.3. Cross-Modal Perception of Duration, Beat, Tempo, and Rhythmic Grouping

Music involves more than just the perception of single durations; the ability to extract beat and tempo from the acoustic stream is a prerequisite to grasping rhythmic and melodic shape, as well as the music's expressive character. A sense of beat can be extracted from a continuous visual stimulus (Grahn 2012), and a bouncing point-light figure paired with a simple auditory beat can influence the perceived location of on-beat versus off-beat accents, that is, the metrical structure of the beat sequence (Su 2014). Similarly, patterns of bodily movement can bias the perceptual organization of an ambiguous rhythm, and this bias is retained when the rhythm is subsequently heard in a nonmovement condition. Phillips-Silver & Trainor (2007, p. 533) hypothesized that "the movement-sound interaction develops early and is fundamental to music processing throughout life." Thus, movement—whether observed, felt, or both—can affect the perception of beats, as well as their metric organization. This may be a fairly subtle effect: As Brochard et al. (2003) have shown, we tend to impose a sense of strong and weak alteration on a series of beats in the absence of any other cues (what they call the tick-tock phenomenon), and thus visual arrays may serve to bias our pre-existing tendency to impose a subjective sense of meter on an otherwise undifferentiated series of pulses.

The perceived rate at which pulses occur can also be influenced by visual information. Observing an accelerating or decelerating pattern of moving dots (which give rise to a sense of optic flow) can bias our sense of the tempo of a concurrent auditory sequence (Su & Jonikaitis 2011). In a somewhat more ecologically valid context, when participants listened to classic rhythm-and-blues songs and watched a stick figure animation (created from motion capture data of a human dancer),

a vigorous dance interpretation led to faster tempo ratings for the music than did a relaxed dance interpretation or the music alone (London et al. 2016). Both dance interpretations were synchronized with the musical beat, and the vigorous dance interpretations were characterized by greater total acceleration, adding support to Luck & Sloboda's (2009) findings regarding the salience of acceleration in a continuous visual display as a rhythmic cue.

Research in the cognitive neuroscience of music in general and in rhythm and movement in particular has grown exponentially over the past two decades. Questions that originated within the domains of philosophy and music theory can now be investigated using modern experimental approaches. The advent of digital recording, which allows for the easy creation, manipulation, and preservation of musical stimuli, has enabled far more rigorous experimentation than had been possible 20 years ago. Coupling advances in neuroimaging techniques with the continuing application of methods from psychophysics and social psychology has created a golden age of music psychology research.

Over the next 10 years, we anticipate major advances in our understanding of the neurophysiological underpinnings of musical behaviors, especially from converging methods in the time domain (EEG, magnetoencephalography) and the spatial domain (positron emission tomography, fMRI). An especially promising area is the neurochemistry of music (e.g., Chanda & Levitin 2013, Mallik et al. 2017), and we hope that more researchers will undertake experiments that selectively target specific neurochemical systems. If we look farther into the future, mapping the connectome of human brains will help to map the connections between neurons and promises to inform a deeper understanding of musical behaviors than chemistry or anatomy alone can reveal. Perhaps chief among the major unanswered questions are what the evolutionary basis of music may be, what the connection between music and health outcomes is, and what makes some musical compositions more memorable and enjoyable than others. We believe that the answers to these questions may be on the horizon, as evidenced by the broad range of disciplinary backgrounds represented at scientific meetings and in the journals devoted to music perception and cognition—psychologists are collaborating with music theorists, economists, archeologists, biologists, chemists, radiologists, anthropologists, nurses, psychiatrists, otolaryngologists, and professional musicians, to name just a few. Many of the unanswered questions that linger will benefit from this type of collaborative, team-based approach, and we look forward to the results of these richly interdisciplinary studies.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

LITERATURE CITED

Abel SM. 1972. Duration discrimination of noise and tone bursts. *J. Acoust. Soc. Am.* 51(4B):1219–23

Abrams DA, Ryali S, Chen T, Chordia P, Khouzam A, et al. 2013. Inter-subject synchronization of brain responses during natural music listening. *Eur. J. Neurosci.* 37(9):1458–69

Adkins A, Kurstin G. 2015. Hello. Recorded by Adele, *25*. London: XL Recordings

Allen GD. 1975. Speech rhythms: its relation to performance universals and articulatory timing. *J. Phon.* 3(2):75–86

Becker W, Fagen D. 1973. Bodhisattva. Recorded by Steely Dan, *Countdown to Ecstasy*. Los Angeles: ABC Records

Bergeson TR, Trehub SE. 2002. Absolute pitch and tempo in mothers' songs to infants. *Psychol. Sci.* 13:72–75

Besson M, Schön D. 2001. Comparison between language and music. *Ann. N. Y. Acad. Sci.* 930(1):232–58

Bhatara A, Tirovolas AK, Duan LM, Levy B, Levitin DJ. 2011. Perception of emotional expression in musical performance. *J. Exp. Psychol. Hum. Percept. Perform.* 37(3):921–34

Bhattacharya J, Petsche H. 2005. Phase synchrony analysis of EEG during music perception reveals changes in functional connectivity due to musical expertise. *Signal Process.* 85(11):2161–77

Brochard R, Abecasis D, Potter D, Ragot R, Drake C. 2003. The "ticktock" of our internal clock: direct brain evidence of subjective accents in isochronous sequences. *Psychol. Sci.* 14(4):362–66

Burger B, Thompson MR, Luck G, Saarikallio S, Toiviainen P. 2013. Influences of rhythm- and timbre-related musical features on characteristics of music-induced movement. *Front. Psychol.* 4:183

Burghardt H. 1973. Die subjektive Dauer schmalbandiger Schalle bei verschiedenen Frequenzlagen. *Acustica* 28:278–84

Butterfield MW. 2010. Participatory discrepancies and the perception of beats in jazz. *Music Percept.* 27:157–76

Cage J. 2011 (1961). *Silence: Lectures and Writings*. Middletown, CT: Wesleyan Univ. Press

Cameron DJ, Grahn JA. 2014. Neuroscientific investigations of musical rhythm. *Acoust. Aust.* 42(2):111

Cameron DJ, Pickett KA, Earhart GM, Grahn JA. 2016. The effect of dopaminergic medication on beat-based auditory timing in Parkinson's disease. *Front. Neurol.* 7:19

Carr KW, Tierney A, White-Schwoch T, Kraus N. 2016. Intertrial auditory neural stability supports beat synchronization in preschoolers. *Dev. Cogn. Neurosci.* 17:76–82

Carr KW, White-Schwoch T, Tierney A, Strait DL, Kraus N. 2014. Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *PNAS* 111(40):14559–64

Chanda ML, Levitin DJ. 2013. The neurochemistry of music. *Trends Cogn. Sci.* 17(4):79–93

Chemin B, Mouraux A, Nozaradan S. 2014. Body movement selectively shapes the neural representation of musical rhythms. *Psychol. Sci.* 25:2147–59

Chen JL, Penhune VB, Zatorre RJ. 2008a. Listening to musical rhythms recruits motor regions of the brain. *Cereb. Cortex* 18(12):2844–54

Chen JL, Penhune VB, Zatorre RJ. 2008b. Moving on time: brain network for auditory-motor synchronization is modulated by rhythm complexity and musical training. *J. Cogn. Neurosci.* 20(2):226–39

Chen JL, Zatorre RJ, Penhune VB. 2006. Interactions between auditory and dorsal premotor cortex during synchronization to musical rhythms. *NeuroImage* 32:1771–81

Chopin F. 1839. Piano Sonata No. 2, Op. 35

Clark R, Resnick A. 1966. Good Lovin'. Recorded by The Rascals, *The Young Rascals*. New York: Atlantic Records

Cohen J. 1954. The experience of time. *Acta. Psychol.* 10:207–19

Colavita FB. 1974. Human sensory dominance. *Atten. Percept. Psychophys.* 16(2):409–12

Collyer CE, Broadbent HA, Church RM. 1994. Preferred rates of repetitive tapping and categorical time production. *Atten. Percept. Psychophys.* 55(4):443–53

Cook P, Rouse A, Wilson M, Reichmuth CJ. 2013. A California sea lion (*Zalophus californianus*) can keep the beat: motor entrainment to rhythmic auditory stimuli in a non vocal mimic. *J. Comp. Psychol.* 127:1–16

Cope TE, Grube M, Singh B, Burn DJ, Griffiths TD. 2014. The basal ganglia in perceptual timing: timing performance in multiple system atrophy and Huntington's disease. *Neuropsychologia* 52(100):73–81

Cross I. 2005. Music and meaning, ambiguity and evolution. In *Musical Communication*, ed. D Miell, R MacDonald, DJ Hargreaves, pp. 27–43. Oxford, UK: Oxford Univ. Press

Day S. 2005. Some demographic and socio-cultural aspects of synesthesia. In *Synesthesia: Perspectives from Cognitive Neuroscience*, ed. L Robertson, N Sagiv, pp. 11–33. Oxford, UK: Oxford Univ. Press

Diaconescu AO, Hasher L, McIntosh AR. 2013. Visual dominance and multisensory integration changes with age. *NeuroImage* 65:152–66

Drake C, Botte MC. 1993. Tempo sensitivity in auditory sequences: evidence for a multiple-look model. *Atten. Percept. Psychophys.* 54(3):277–86

Drake C, Gros L, Penel A. 1999. How fast is that music? The relation between physical and perceived tempo. In *Music, Mind, and Science*, ed. SW Yi, pp. 190–203. Seoul, South Korea: Seoul Univ. Press

Drake C, Jones MR, Baruch C. 2000. The development of rhythmic attending in auditory sequences: attunement, referent period, focal attending. *Cognition* 77:251–88

Eck D. 2002. Finding downbeats with a relaxation oscillator. *Psychol. Res.* 66(1):18–25

Eerola T, Luck G, Toiviainen P. 2006. An investigation of pre-schoolers' corporeal synchronization with music. *Proc. Int. Conf. Music Percept. Cogn.*, *9th*, *Bologna, Italy*, pp. 472–76. Bologna, Italy: Soc. Music Percept. Cogn./Eur. Soc. Cogn. Sci. Music

Fechner GT. 1860. *Elemente der Psychophysik*. Leipzig, Ger.: Breitkopf und Härtel

Franěk M, Van Noorden L, Režný L. 2014. Tempo and walking speed with music in the urban context. *Front. Psychol.* 5:1361

Friberg A, Sundberg J. 1993. Perception of just noticeable time displacement of a tone presented in a metrical sequence at different tempos. In *Quarterly Progress and Status Report*, ed. Kunglinga Tek. Högsk. Speech Transm. Lab., pp. 49–55. Stockholm: R. Inst. Technol.

Friberg A, Sundberg J. 1995. Time discrimination in a monotonic, isochronous sequence. *J. Acoust. Soc. Am.* 98(5):2524–31

Friberg A, Sundströöm A. 2002. Swing ratios and ensemble timing in jazz performance: evidence for a common rhythmic pattern. *Music Percept.* 19(3):333–49

Fruhauf J, Kopiez R, Platz F. 2013. Music on the timing grid: the influence of microtiming on the perceived groove quality of a simple drum pattern performance. *Music Sci.* 17(2):246–60

Fujioka T, Ross B, Trainor LJ. 2015. Beta-band oscillations represent auditory beat and its metrical hierarchy in perception and imagery. *J. Neurosci.* 35:15187–98

Gjerdingen RO. 1994. Apparent motion in music? *Music Percept.* 11(4):335–70

Glass L, Mackey MC. 1988. *From Clocks to Chaos: The Rhythms of Life*. Princeton, NJ: Princeton Univ. Press

Grahn JA. 2012. See what I hear? Beat perception in auditory and visual rhythms. *Exp. Brain Res.* 220(1):51–61

Grahn JA, Brett M. 2007. Rhythm perception in motor areas of the brain. *J. Cogn. Neurosci.* 19(5):893–906

Grahn JA, Brett M. 2009. Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex* 45(1):54–61

Grahn JA, Henry MJ, McAuley JD. 2011. FMRI investigation of cross-modal interactions in beat perception: Audition primes vision, but not vice versa. *NeuroImage* 54:1231–43

Grahn JA, Rowe JB. 2009. Feeling the beat: premotor and striatal interactions in musicians and non-musicians during beat processing. *J. Neurosci.* 29(23):7540–48

Grahn JA, Rowe JB. 2012. Finding and feeling the musical beat: striatal dissociations between detection and prediction of regularity. *Cereb Cortex* 23(4):913–21

Gratton I, Brandimonte MA, Bruno N. 2016. Absolute memory for tempo in musicians and non-musicians. *PLOS ONE* 11(10):e0163558

Griffiths TD, Warren JD, Scott SK, Nelken I, King AJ. 2004. Cortical processing of complex sound: a way forward? *Trends Neurosci*. 27(4):181–85

Grondin S, McAuley JD. 2009. Duration discrimination in crossmodal sequences. *Perception* 38(10):1542–59

Halpern AR, Andrews MW. 2008. Melody recognition at fast and slow tempos: effects of age, experience, and familiarity. *Atten. Percept. Psychophys.* 70:496–502

Halpern AR, Müllensiefen D. 2008. Effects of timbre and tempo change on memory for music. *Q. J. Exp. Psychol.* 61(9):1371–84

Hancock H. 1973. Chameleon. Recorded by Herbie Hancock, *Headhunters*. New York: Columbia Records

Hasegawa A, Okanoya K, Hasegawa T, Seki Y. 2011. Rhythmic synchronization tapping to an audio-visual metronome in budgerigars. *Sci. Rep.* 1:120

Hattori Y, Tomonaga M, Matsuzawa T. 2013. Spontaneous synchronized tapping to an auditory rhythm in a chimpanzee. *Sci. Rep.* 3:1566

Henry MJ, Herrmann B, Grahn JA. 2017. What can we learn about beat perception by comparing brain signals and stimulus envelopes? *PLOS ONE* 12(2):e0172454

Hibi S. 1983. Rhythm perception in repetitive sound sequence. *J. Acoust. Soc. Jpn.* 4:83–95

Himberg T. 2014. *Interaction in Musical Time*. PhD Thesis, Univ. Cambridge, UK

Hirsh I, Sherrick C. 1961. Perceived order in difference sense modalities. *J. Exp. Psychol.* 62:423–32

Houlihan K, Levitin DJ. 2011. *Recognition of melodies from rhythm and pitch*. Presented at Bi-Annu. Meet. Soc. Music Percept. Cogn., Rochester, NY

Hove MJ, Balasubramaniam R, Keller PE. 2014. The time course of phase correction: a kinematic investigation of motor adjustment to timing perturbations during sensorimotor synchronization. *J. Exp. Psychol. Hum. Percept. Perform.* 40:2243–51

Hove MJ, Iversen JR, Zhang A, Repp BH. 2013. Synchronization with competing visual and auditory rhythms: Bouncing ball meets metronome. *Psychol. Res.* 77(4):388–98

Huron D. 2006. *Sweet Anticipation: Music and the Psychology of Expectation*. Cambridge, MA: MIT Press

Iversen JR, Patel AD, Nicodemus B, Emmorey K. 2015. Synchronization to auditory and visual rhythms in hearing and deaf individuals. *Cognition* 134:232–44

Iversen JR, Repp BH, Patel AD. 2009. Top-down control of rhythm perception modulates early auditory responses. *Ann. N. Y. Acad. Sci.* 1169:58–73

Iyer V. 2002. Embodied mind, situated cognition, and expressive microtiming in African-American music. *Music Percept.* 19(3):387–414

Jackson M. 1983. Beat It. Recorded by Michael Jackson, *Thriller*. New York: Epic Records

Janata P, Tomic ST, Haberman J. 2012. Sensorimotor coupling in music and the psychology of the groove. *J. Exp. Psychol. Gen.* 141(1):54–75

Jeannerod M. 2006. *Motor Cognition: What Actions Tell to the Self*. Oxford, UK: Oxford Univ. Press

Jeon JY, Fricke FR. 1997. Duration of perceived and performed sounds. *Psychol. Music* 25(1):70–83

Judkis M. 2011. World's longest concert will last 639 years. *The Washington Post*, November 21. **https://www.washingtonpost.com/blogs/arts-post/post/worlds-longest-concert-will-last-639-years/2011/11/21/gIQAWrdXiN_blog.html**

Keil C. 1987. Participatory discrepancies and the power of music. *Cult. Anthropol.* 2:275–83

Konvalinka I, Vuust P, Roepstorff A, Frith CD. 2010. Follow you, follow me: continuous mutual prediction and adaptation in joint tapping. *Q. J. Exp. Psychol.* 63:2220–30

Korte A. 1915. Kinematoskopische Untersuchungen [Cinematoscopic investigations]. *Z. Psychol.* 72:193–296

Kosonen K, Raisamo R. 2006. Rhythm perception through different modalities. *Proc. Eurohaptics, July 3–6, Paris*, pp. 365–70. Aarhus, Den.: Interact. Des. Found.

Kuchenbuch A, Paraskevopoulos E, Herholz SC, Pantev C. 2012. Electromagnetic correlates of musical expertise in processing of tone patterns. *PLOS ONE* 7(1):e30171

Kung SJ, Chen JL, Zatorre RJ, Penhune VB. 2013. Interacting cortical and basal ganglia networks underlying finding and tapping to the musical beat. *J. Cogn. Neurosci.* 25(3):401–20

Lametti DR, Ostry DJ. 2010. Postural constraints on movement variability. *J. Neurophys.* 104(2):1061–67

Langer S. 1953. *Feeling and Form*. New York: Scribners

Large EW. 2008. Resonating to musical rhythm: theory and experiment. In *Psychology of Time*, ed. S Grondin, pp. 189–232. Bingley, UK: Emerald

Large EW, Almonte F, Velasco M. 2010. A canonical model for gradient frequency neural networks. *Physica D* 239:905–11

Large EW, Gray PM. 2015. Spontaneous tempo and rhythmic entrainment in a bonobo (*Pan paniscus*). *J. Comp. Psychol.* 129(4):317–28

Large EW, Kolen JF. 1994. Accent structures in music performance. *Connect. Sci.* 6:177–208

Large EW, Palmer C. 2002. Perceiving temporal regularity in music. *Cogn. Sci.* 26:1–37

Leman M, Maes PJ. 2015. The role of embodiment in the perception of music. *Empir. Music. Rev.* 9(3–4):236–46

Leman M, Moelants D, Varewyck M, Styns F, van Noorden L, Martens JP. 2013. Activating and relaxing music entrains the speed of beat synchronized walking. *PLOS ONE* 8(7):e67932

Leow LA, Parrott T, Grahn JA. 2014. Individual differences in beat perception affect gait responses to low- and high-groove music. *Front. Hum. Neurosci.* 8:811

Leow LA, Rinchon VE, Grahn JA. 2015. Familiarity with music increases walking speed in rhythmic auditory cueing. *Ann. N. Y. Acad. Sci.* 1337:53–61

Levitin DJ. 1999. Tone deafness: failures of musical anticipation and self-reference. *Int. J. Comput. Anticip. Syst.* 4:243–54

Levitin DJ, Cook PR. 1996. Memory for musical tempo: additional evidence that auditory memory is absolute. *Atten. Percept. Psychophys.* 58(6):927–35

Levitin DJ, McAdams S, Adams RL. 2002. Control parameters for musical instruments: a foundation for new mappings of gesture to sound. *Organ. Sound* 7(2):171–89

Levitin DJ, Menon V. 2003. Musical structure is processed in "language" areas of the brain: a possible role for Brodmann Area 47 in temporal coherence. *NeuroImage* 20(4):2142–52

Levitin DJ, Rogers SE. 2005. Absolute pitch: perception, coding, and controversies. *Trends Cogn. Sci.* 9(1):26–33

London J. 2011. Tactus ≠ tempo: some dissociations between attentional focus, motor behavior. *Empir. Musicol. Rev.* 6(1):43–55

London J, Burger B, Thompson M, Toiviainen P. 2016. Speed on the dance floor: auditory and visual cues for musical tempo. *Acta Psychol.* 164:70–80

London JM. 1993. Loud rests and other strange metric phenomena (or, meter as heard). *Music Theory Online* 0(2):1067–3040

London JM. 2012. *Hearing in Time: Psychological Aspects of Musical Meter*. Oxford, UK: Oxford Univ. Press. 2nd ed.

Luck G, Sloboda JA. 2009. Spatio-temporal cues for visually mediated synchronization. *Music Percept.* 26(5):465–73

Madison G. 2006. Experiencing groove induced by music: consistency and phenomenology. *Music Percept.* 24(2):201–8

Madison G, Sioros G. 2014. What musicians do to induce the sensation of groove in simple and complex melodies, and how listeners perceive it. *Front. Psychol.* 5:894

Mallik A, Chanda ML, Levitin DJ. 2017. Anhedonia to music and mu-opioids: evidence from the administration of naltrexone. *Sci. Rep.* 7:41952

Manning F, Schutz M. 2013. "Moving to the beat" improves timing perception. *Psychon. B* 20:1133–39

Manning FC, Schutz M. 2016. Trained to keep a beat: movement-related enhancements to timing perception in percussionists and non-percussionists. *Psychol. Res.* 80(4):532–42

Martens PA. 2011. The ambiguous tactus: tempo, subdivision, benefits, and three listener strategies. *Music Percept.* 28(5):433–48

Martin JH. 2005. The corticospinal system: from development to motor control. *Neuroscientist* 11(2):161–73

Mates J, Muller U, Radil T, Poppel E. 1994. Temporal integration in sensorimotor synchronization. *J. Cogn. Neurosci.* 6(4):332–40

Mbongwana Star. 2015. Malukayi. Recorded by Mbongwana Star, *From Kinshasa*. London: World Circuit

McAuley JD. 2010. Tempo and rhythm. In *Music Perception*, ed. MR Jones, pp. 165–99. New York: Springer

McAuley JD, Henry MJ, Tkach J. 2012. Tempo mediates the involvement of motor areas in beat perception. *Ann. N. Y. Acad. Sci.* 1252(1):77–84

McAuley JD, Jones MR, Holub S, Johnston HM, Miller NS. 2006. The time of our lives: life span development of timing and event tracking. *J. Exp. Psychol. Gen.* 135(3):348–67

McGurk H, MacDonald J. 1976. Hearing lips and seeing voices. *Nature* 264:746–48

McNeill W. 1995. *Keeping Together in Time: Dance and Drill in Human History*. Cambridge, MA: Harvard Univ. Press

Mendonça C, Oliveira M, Fontes L, Santos J. 2014. The effect of instruction to synchronize over step frequency while walking with auditory cues on a treadmill. *Hum. Mov. Sci.* 33:33–42

Merchant H, Honing H. 2014. Are non-human primates capable of rhythmic entrainment? Evidence for the gradual audiomotor evolution hypothesis. *Front. Neurosci.* 7:274

Merchant H, Pérez O, Zarco W, Gámez J. 2013. Interval tuning in the primate medial premotor cortex as a general timing mechanism. *J. Neurosci.* 33(21):9082–96

Miller NS, McAuley JD. 2005. Tempo sensitivity in isochronous tone sequences: the multiple-look model revisited. *Percept. Psychophys.* 67(7):1150–60

Mills PF, van der Steen MC, Schultz BG, Keller PE. 2015. Individual differences in temporal anticipation and adaptation during sensorimotor synchronization. *Timing Time Percept.* 3(1–2):13–31

Mitchell J. 1970. Woodstock. Recorded by Crosby, Stills, Nash & Young, *Déjà Vu*. New York: Atlantic Records

Mitrani L, Shekerdijiiski S, Yakimoff N. 1986. Mechanisms and asymmetries in visual perception of simultaneity and temporal order. *Biol. Cybernet.* 54:159–65

Näätänen R, Paavilainen P, Rinne T, Alho K. 2007. The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clin. Neurophysiol.* 118(12):2544–90

Nowicki L, Prinz W, Grosjean M, Repp BH, Keller PE. 2013. Mutual adaptive timing in interpersonal action coordination. *Psychomusicol. Music Mind Brain* 23:6–20

Nozaradan S, Peretz I, Missal M, Mouraux A. 2011. Tagging the neuronal entrainment to beat and meter. *J. Neurosci.* 31:10234–40

Nozaradan S, Peretz I, Mouraux A. 2012. Selective neuronal entrainment to the beat and meter embedded in a musical rhythm. *J. Neurosci.* 32:17572–81

Palmer C, Lidji P, Peretz I. 2014. Losing the beat: deficits in temporal coordination. *Philos. Trans. R. Soc. B* 369:20130405

Parker C. 1949. Bird Gets the Worm. Recorded by Charlie "Bird" Parker, *Bird Gets the Worm*. Newark, NJ: Savoy Records

Patel AD. 2006. Musical rhythm, linguistic rhythm, and human evolution. *Music Percept.* 24:99–104

Patel AD, Iversen JR. 2014. The evolutionary neuroscience of musical beat perception: the Action Simulation for Auditory Prediction (ASAP) hypothesis. *Front. Sys. Neurosci.* 8:57

Patel AD, Iversen JR, Bregman MR, Schulz I. 2009. Experimental evidence for synchronization to a musical beat in a nonhuman animal. *Curr. Biol.* 19(10):827–30

Pecenka N, Keller PE. 2011. The role of temporal prediction abilities in interpersonal sensorimotor synchronization. *Exp. Brain. Res.* 211(3):505–15

Petrides M, Pandya DN. 2002. Comparative cytoarchitectonic analysis of the human and the macaque ventrolateral prefrontal cortex and corticocortical connection patterns in the monkey. *Eur. J. Neurosci.* 16(2):291–310

Phillips-Silver J, Toiviainen P, Gosselin N, Piché O, Nozaradan S, et al. 2011. Born to dance but beat deaf: a new form of congenital amusia. *Neuropsychologia* 49:961–69

Phillips-Silver J, Trainor LJ. 2005. Feeling the beat: Movement influences infant rhythm perception. *Science* 308:1430

Phillips-Silver J, Trainor LJ. 2007. Hearing what the body feels: auditory encoding of rhythmic movement. *Cognition* 105:533–46

Phillips-Silver J, Trainor LJ. 2008. Vestibular influence on auditory metrical interpretation. *Brain Cogn.* 67(1):94–102

Poon M, Schutz M. 2015. Cueing musical emotions: An empirical analysis of 24-piece sets by Bach and Chopin documents parallels with emotional speech. *Front. Psychol.* 6:1419

Posner MI, Nissen MJ, Klein RM. 1976. Visual dominance: an information-processing account of its origins and significance. *Psychol. Rev.* 83(2):157–71

Povel DJ. 1981. Internal representation of simple temporal patterns. *J. Exp. Psychol. Hum. Percept. Perform.* 7(1):3–18

Radiohead. 1997. Paranoid Android. Recorded by Radiohead, *OK Computer*. London: Parlophone

Repp BH. 2000. Subliminal temporal discrimination revealed in sensorimotor coordination. In *Rhythm Perception and Production*, ed. P Desain, WL Windsor, pp. 129–42. Lisse: Swets & Zeitlinger

Repp BH. 2002. Phase correction following a perturbation in sensorimotor synchronization depends on sensory information. *J. Mot. Behav.* 34(3):291–98

Repp BH. 2005. Sensorimotor synchronization: a review of the tapping literature. *Psychon. Bull. Rev.* 12:969–92

Repp BH, Doggett R. 2007. Tapping to a very slow beat: a comparison of musicians and non-musicians. *Music Percept.* 24:367–76

Repp BH, Keller PE. 2004. Adaptation to tempo changes in sensorimotor synchronization: effects of intention, attention, and awareness. *Q. J. Exp. Psychol.* 57(3):499–521

Repp BH, Penel A. 2002. Auditory dominance in temporal processing: new evidence from synchronization with simultaneous visual and auditory sequences. *J. Exp. Psychol. Hum. Percept. Perform.* 28(5):1085–99

Repp BH, Su YH. 2013. Sensorimotor synchronization: a review of recent research (2006–2012). *Psychon. Bull. Rev.* 20:403–52

Roholt T. 2014. *Groove: A Phenomenology of Musical Nuance*. New York: Bloomsbury

Rosch E. 1978. Principles of categorization. In *Cognition and Categorization*, Vol. 1, ed. E Rosch, BB Lloyd, pp. 27–48. Hillsdale, NJ: Lawrence Erlbaum Assoc.

Rouse AA, Cook PF, Large EW, Reichmuth C. 2016. Beat keeping in a sea lion as coupled oscillation: implications for comparative understanding of human rhythm. *Front. Neurosci.* 10:257

Salmelin R, Hari R. 1994. Spatiotemporal characteristics of sensorimotor neuromagnetic rhythms related to thumb movements. *Neuroscience* 60:537–50

Schachner A, Brady TF, Pepperberg IM, Hauser MD. 2009. Spontaneous motor entrainment to music in multiple vocal mimicking species. *Curr. Biol.* 19(10):831–36

Scharf B, Buus S. 1986. Audition. In *Handbook of Perception and Human Performance*, Vol. 1, ed. KR Boff, L Kaufman, JP Thomas, pp. 14-1–14-71. Hoboken, NJ: Wiley

Schulkind MD. 1999. Long-term memory for temporal structure: evidence from the identification of well-known and novel songs. *Mem. Cogn.* 27(5):896–906

Schuller G. 1968. *Early Jazz: Its Roots and Musical Development*. Oxford, UK: Oxford Univ. Press

Schutz M, Kubovy M. 2009. Causality and cross-modal integration. *J. Exp. Psychol. Hum. Percept. Perform.* 35(6):1791–810

Schutz M, Lipscomb S. 2007. Hearing gestures, seeing music: Vision influences perceived tone duration. *Perception* 36(6):888–97

Schwartze M, Keller PE, Patel AD, Kotz SA. 2011. The impact of basal ganglia lesions on sensorimotor synchronization, spontaneous motor tempo, and the detection of tempo changes. *Behav. Brain Res.* 216(2):685–91

Selezneva E, Deike S, Knyazeva S, Scheich H, Brechmann A, Brosch M. 2013. Rhythm sensitivity in macaque monkeys. *Front. Syst. Neurosci.* 7:49

Senn O, Kilchenmann L, Von Georgi R, Bullerjahn C. 2016. The effect of expert performance microtiming on listeners' experience of groove in swing or funk music. *Front. Psychol.* 7:1487

Sevdalis V, Keller PE. 2014. Know thy sound: perceiving self and others in musical contexts. *Acta Psychol.* 152:67–74

Shiffrar M. 2005. Movement and event perception. In *The Blackwell Handbook of Perception and Cognition*, ed. EB Goldstein, pp. 237–71. Hoboken, NJ: Wiley

Sowiński J, Dalla Bella S. 2013. Poor synchronization to the beat may result from deficient auditory-motor mapping. *Neuropsychologia* 51(10):1952–63

Styns F, van Noorden L, Moelants D, Leman M. 2007. Walking on music. *Hum. Mov. Sci.* 26(5):769–85

Su YH. 2014. Audiovisual beat induction in complex auditory rhythms: point-light figure movement as an effective visual beat. *Acta Psychol.* 151:40–50

Su YH, Jonikaitis D. 2011. Hearing the speed: Visual motion biases the perception of auditory tempo. *Exp. Brain Res.* 214(3):357–71

Su YH, Pöppel E. 2012. Body movement enhances the extraction of temporal structures in auditory sequences. *Psychol. Res.* 76(3):373–82

Su YH, Salazar-López E. 2016. Visual timing of structured dance movements resembles auditory rhythm perception. *Neural Plast.* 2016:1678390

Swaminathan S, Schellenberg EG. 2015. Current emotion research in music psychology. *Emot. Rev.* 7(2):189–97

Talsma D, Senkowski D, Woldorff MG. 2009. Intermodal attention affects the processing of the temporal alignment of audiovisual stimuli. *Exp. Brain Res.* 198(2–3):313–28

Teki S, Grube M, Kumar S, Griffiths TD. 2011. Distinct neural substrates of duration-based and beat-based auditory timing. *J. Neurosci.* 31:3805–12

Thomson JM, Fryer B, Maltby J, Goswami U. 2006. Auditory and motor rhythm awareness in adults with dyslexia. *J. Res. Read.* 29:334–48

Thomson JM, Goswami U. 2008. Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *J. Physiol. Paris* 102:120–29

Thompson WF. 2014. *Music in the Social and Behavioral Sciences: An Encyclopedia*. Thousand Oaks, CA: SAGE Publ.

Tierney A, Kraus N. 2013. The ability to tap to a beat relates to cognitive, linguistic, and perceptual skills. *Brain Lang.* 124:225–31

Toiviainen P, Luck G, Thompson MR. 2010. Embodied meter: hierarchical eigenmodes in music-induced movement. *Music Percept.* 28:59–70

Toiviainen P, Snyder JS. 2003. Tapping to Bach: resonance-based model of pulse. *Music Percept.* 21(1):43–80

Trainor LJ, Gao X, Lei JJ, Lehtovaara K, Harris LR. 2009. The primal role of the vestibular system in determining musical rhythm. *Cortex* 45(1):35–43

van der Steen MC, Schwartze M, Kotz SA, Keller PE. 2015. Modeling effects of cerebellar and basal ganglia lesions on adaptation and anticipation during sensorimotor synchronization. *Ann. N. Y. Acad. Sci.* 1337(1):101–10

van Noorden L, Moelants D. 1999. Resonance in the perception of musical pulse. *J. New Music Res.* 28(1):43–66

Varèse E, Wen-Chung C. 1966. The liberation of sound. *Perspect. New Music* 5(1):11–19

Varlet M, Marin L, Issartel J, Schmidt RC, Bardy BG. 2012. Continuity of visual and auditory rhythms influences sensorimotor coordination. *PLOS ONE* 7(9):e44082

Vines BW, Krumhansl CL, Wanderley MM, Dalca IM, Levitin DJ. 2011. Music to my eyes: cross-modal interactions in the perception of emotions in musical performance. *Cognition* 118(2):157–70

Von Ehrenfels CF. 1988 (1890). On "gestalt qualities". In *Foundations of Gestalt Theory*, ed. B Smith, pp. 14–17. Munich: Philosophia Verlag

von Helmholtz H. 1954 (1863). *On the Sensations of Tone*. New York: Dover

Vuust P, Roepstorff A, Wallentin M, Mouridsen K, Ostergaard L. 2006. It don't mean a thing. . . Keeping the rhythm during polyrhythmic tension activates language areas (BA47). *NeuroImage* 31:832–41

Warren RM, Gardner DA, Brubaker BS, Bashford JA Jr. 1991. Melodic and nonmelodic sequences of tones: effects of duration on perception. *Music Percept*. 8:277–90

Welch B. 1973. Hypnotized. Recorded by Fleetwood Mac, *Mystery to Me*. Burbank: Reprise Records

Wing AM, Endo S, Bradbury A, Vorberg D. 2014. Optimal feedback correction in string quartet synchronization. *J. R. Soc.* 11(93):20131125

Winkler I, Háden GP, Ladinig O, Sziller I, Honing H. 2009. Newborn infants detect the beat in music. *PNAS* 106:2468–71

Witek MA, Clarke EF, Wallentin M, Kringelbach ML, Vuust P. 2014. Syncopation, body-movement and pleasure in groove music. *PLOS ONE* 9(4):e94446

Zarco W, Merchant H, Prado L, Mendez JC. 2009. Subsecond timing in primates: comparison of interval production between human subjects and rhesus monkeys. *J. Neurophysiol*. 102(6):3191–202

Zentner M, Eerola T. 2010. Rhythmic engagement with music in infancy. *PNAS* 107(13):5768–73

ANNUAL REVIEWS
Connect With Our Experts
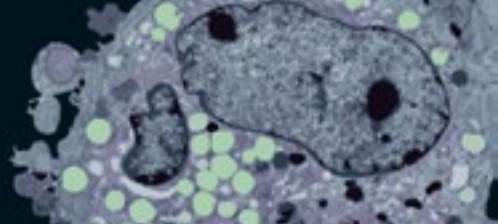
New From Annual Reviews:

Annual Review of Cancer Biology
cancerbio.annualreviews.org • Volume 1 • March 2017

ONLINE NOW!

Co-Editors: Tyler Jacks, *Massachusetts Institute of Technology*

Charles L. Sawyers, *Memorial Sloan Kettering Cancer Center*

The *Annual Review of Cancer Biology* reviews a range of subjects representing important and emerging areas in the field of cancer research. The *Annual Review of Cancer Biology* includes three broad themes: Cancer Cell Biology, Tumorigenesis and Cancer Progression, and Translational Cancer Science.

Contents

Indexes

Errata

An online log of corrections to *Annual Review of Psychology* articles may be found at
http://www.annualreviews.org/errata/psych