The Science-Music Borderlands

Reckoning with the Past and Imagining the Future

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6 Music, Mind, Body, and World

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Sirens Behave so Strangely

What is the difference between song and speech? Between musical and nonmusical sound? These differences are commonly explained in terms of sonic features: for example, singing has more sustained pitches than speaking, more temporal regularity, and more exact repetition. In this view, a sound's musicality depends on its inherent, objective properties. But certain sounds can blur the boundary between these categories or even move from one to the other.

In 1857, Hermann von Helmholtz gave a public lecture in Bonn titled "On the Physiological Causes of Harmony in Music." It examined "musical sounds and sensations" and introduced recent research in "physical and physiological acoustics" (Helmholtz, 1995, pp. 46–47). Such lectures were a kind of popular science. Helmholtz was teaching general audiences about specific findings but also about science itself—how it was done and what it could do (Cahan, 1993; Steege, 2012). So, as he discussed sound waves and the structure of the ear, Helmholtz also described devices for producing and studying tone, including tuning forks, resonators, and the mechanical siren (for a discussion of tuning forks and nineteenth-century psychology, see Raz's chapter 5 in this volume). The siren blows air through holes punched in a rotating disc. At a slow speed, the resulting puffs of air create a rhythm; at higher speeds, they coalesce into a tone. This demonstrates a surprising continuity between rhythm and pitch (Rehding, 2016). Yet for Helmholtz, it also revealed a paradox:

> When the siren is turned slowly, and hence the puffs of air succeed each other slowly, you hear no musical sound. By the continually increasing rapidity of its revolution, no essential change is produced in the kind of vibration of the air. Nothing new happens externally to the ear. The only new result is the sensation experienced by the ear. . . . If you admire paradoxes, you may say that aerial vibrations do not become sound until they fall upon a hearing ear. (1995, p. 52)

Musical sound, then, does not simply exist in the physical world; it also involves human physiology and psychology.

The siren's tone recalls other pitch phenomena that are partially constituted by a listener's mind. In the speech-to-song illusion, a spoken phrase—most famously, "sometimes behave so strangely"—starts to sound like singing when it is looped (Deutsch, 2019, p. 152). This complicates the objective distinction between speech and song because the shift involves no external sonic change. Other examples include the missing fundamental effect, in which listeners sense a low tone that is not physically present, and Shepard tones, which can create an impossible never-ending ascent or descent because they have a clear pitch class but an indeterminate register. In each case, music emerges in an interaction between sound and mind.

This relation suggests two complementary possibilities. First, if the mind shapes music, then psychology might elucidate questions about musical organization. Insights about perception and cognition might guide new theories of harmony, as Helmholtz supposed, or of other musical elements. Conversely, analyses of musical organization by music theorists, musicologists, and ethnomusicologists might offer distinctive insights about the human mind.

Yet the association between music and mind can sometimes be problematic. In the popular imagination, music is often thought to improve intelligence (despite the debunking of the so-called Mozart effect), and the "genius" composers of Western art music such as Johann Sebastian Bach are considered exemplary minds. For example, one online article states that Bach had an IQ of 165 (Rizzi, 2018). This kind of claim is not new. Almost a hundred years ago, Catharine Morris Cox (1926, pp. 309–310) estimated Bach's IQ at 140, based on biographies by Forkel and Spitta. Even earlier, the nineteenth-century eugenicist Francis Galton (1892)—who designed the first standardized intelligence tests—used Bach and other musicians to support racist theories of "hereditary genius" (for a discussion of music and eugenics, see Cowan's chapter 16 in this volume). The 2018 article does not invoke biography or genetics, though. It seeks evidence of Bach's intelligence in musical patterns from his compositions, particularly numerological devices and the use of the B-A-C-H motif, which translates the letters of his surname into pitches. This implicitly compares Bach's contrapuntal achievements to pattern-based psychometric tests used to measure IQ. It reveals common assumptions about music and mind, approaching both in terms of abstract reasoning.

This chapter pursues a richer, more critical view. The human mind, as revealed in music, is not simply an innate or inherited capacity for abstract reasoning. Rather, it is multifaceted; it is embodied and situated in a world alongside objects and others. Like the tone of Helmholtz's siren, the mind emerges at the boundaries between different levels, shaped by physiology but also experience, culture, and technology. Like music, the mind is inherently relational.

Although this chapter could examine various musical elements (e.g., rhythm, meter, timbre), it focuses on pitch. And although it mentions styles from rock to Balinese gamelan, most of the illustrations are drawn from Bach. This facilitates a discussion of previous literature, where arguably Bach's music is overrepresented. More importantly, while it is imperative to decenter Western art music via cross-cultural research (Jacoby et al., 2020), it is also important to demonstrate that common assumptions are inadequate for this canonical example, which has long been used to support them. Bodies, technologies, or social relations are not only relevant to popular and non-Western musics, for example, and Bach is not some kind of transcendent "disembodied spirit" (Forkel, quoted in De Souza, 2017, p. 109). Even here, music is intertwined with mind, body, and world—and the chapter takes up each of these themes in turn.

Music, Computation, and Language

Cognitive science emerged as an interdisciplinary project in the mid-twentieth century. Inspired by recent technological advances, scholars started to imagine the mind as a computational system (McCulloch & Pitts, 1943). In this view, cognition is a kind of symbolic processing, with mathematics, logic, and language as paradigmatic examples. Linguistic syntax, for instance, was explained through systematic rules, tree-like hierarchies, and deep hidden structures (Chomsky, 1957). How could music fit into this model of the mind?

One computational approach to music cognition was developed by the composer-theorist Fred Lerdahl and the linguist Ray Jackendoff. Their *Generative Theory of Tonal Music* built on Chomskyan linguistics, using preference rules, hierarchies, and abstract deep structure to account for musical features such as harmony and meter (Lerdahl & Jackendoff, 1983). They argue that the brain's "music module, constructing the structure of the music in real time, unconsciously computes its moment-to-moment tensions and attractions" (Jackendoff & Lerdahl, 2006, p. 57). For example, Lerdahl's theory of tonal pitch space offers an algebraic model that quantifies the distance between any two pitches (Lerdahl, 2001). Such distances are hypothetically calculated in a listener's mind. Music, then, takes its place alongside language, revealing the computational mind at work (Jackendoff, 1987).

Figure 6.1 illustrates their approach in Bach's setting of the Lutheran chorale "Christus, der ist mein Leben" (Lerdahl & Krumhansl, 2007). The opening phrase starts from and returns to its tonic F-major chord. Each chord's relation to this tonic is indicated

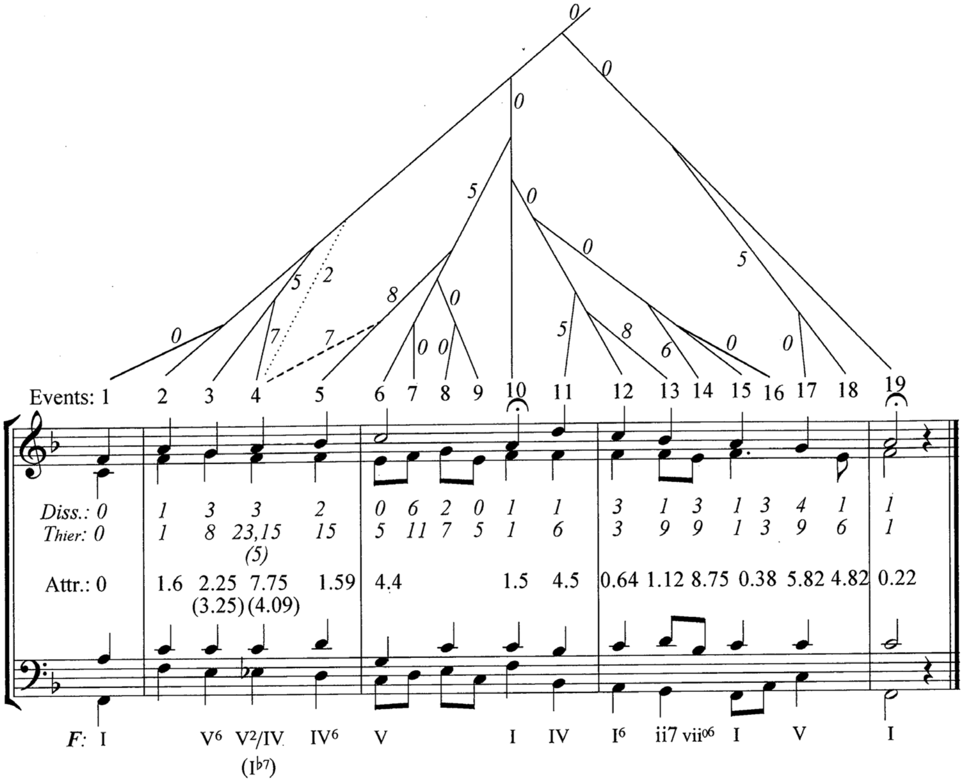

Figure 6.1

Analysis of Bach's "Christus, der ist mein Leben," BWV 281 (Lerdahl & Krumhansl, 2007, fig. 25). "Diss." represents surface dissonance values, "Thier" hierarchical tension values, and "Attr." attraction values.

by a roman-numeral label. But this standard harmonic analysis is supplemented by numeric data for surface dissonance, hierarchical tension, and attraction, generated by the tonal-pitch-space model. A tree diagram above the notation represents each event as a branch. When a branch attaches at a higher position, the corresponding event is more stable and appears at a more abstract level; when it attaches at a lower position, the event is less stable and more ornamental. Event 2 (the tonic on the initial downbeat) anchors the entire phrase, whereas the tense passing motion of event 7 carries little weight. This tree can also be read from left to right: when a longer branch is followed by a shorter one, tonal tension increases; conversely, when a shorter branch is followed by a longer one, tension decreases. For example, tension decreases as event

1's pickup leads to event 2, or at a larger level when the dominant of event 6 resolves to the tonic of event 10. Overall, this analysis connects adjacent and nonadjacent events, suggesting a multilayered process of tonal departure and return.

Empirical studies have collected listeners' ratings of musical tension via stop-tension tasks (where the music stops at an event and participants rate its degree of tension) and continuous-tension tasks (rating the music as it unfolds). With both, ratings from musically trained participants correlated significantly with the model's predictions (Lerdahl & Krumhansl, 2007; see also Bigand et al., 1996; Krumhansl, 1996; Smith & Cuddy, 2003). This suggests that its quantification is consistent with listeners' cognition of tonal syntax. Yet, while responses validate the computational model, they are also used to *refine* it. Its parameters can be adjusted to improve the fit with the empirical data and to compare hypotheses or theoretical interpretations (e.g., different analytical methods provide different metrics for distance in chromatic music). So, the computational model is not static. It proceeds in dialogue with experimental research.

This approach draws on a hierarchical theory of mind but also on an earlier hierarchical theory of music. Heinrich Schenker (1935) developed similar methods of pitch reduction along with a distinctive analytical use of music notation. Broadly speaking, Lerdahl's tree diagram translates a Schenkerian analysis into a Chomskyan form. Schenker himself believed that music needs rules to be comprehensible, and he subscribed to a Kantian epistemology in which the listening mind represents discrete events and synthesizes them into an experiential whole (Korsyn, 1988). For Schenker, tonal hierarchy was natural, produced by the structure of the overtone series. He advocated supremacy of the Germanic canon, and his antidemocratic worldview linked musical, social, and racial hierarchies (Cook, 2007; Ewell, 2020).

By comparison, Lerdahl suggests that music should reflect the "nature" of the mind and that "the best music utilizes the full potential of our cognitive resources" (1992, p. 118; see also Cook, 1999, p. 241). While he considers much Western art music, jazz, Indian classical music, and Japanese koto music to meet these criteria, he dismisses other traditions: "Balinese gamelan falls short with respect to its primitive pitch space. Rock music fails on grounds of insufficient complexity" (1992, p. 119). Much as an IQ test ranks people according to a culturally specific definition of intelligence, this approach ranks musical genres according to culturally specific aesthetic values. Note that these exclusionary claims are offered without evidence. On one level, they are brought into question by scholarship on gamelan (e.g., Perlman, 2004; Tenzer, 2000) and rock (e.g., Temperley, 2018). Yet on another level, these claims are not properly testable. No computational model, no empirical results can prove that certain music or musicians or minds are best.

Naturalizing a particular style should also be avoided, as enculturation is fundamental to music cognition. The participants who rated tension in "Christus, der ist mein Leben" had formal training in Western music (Lerdahl & Krumhansl, 2007). A group with substantially different musical experience would provide different ratings. In an experiment investigating melodic expectations in a traditional Balinese melody, predictions by American musicians were better than chance, but they were substantially less accurate and less confident than those of Balinese musicians (Huron, 2006, pp. 53–55). In another study with Balinese musical stimuli, Westerners' responses reflected the statistical frequency of the melody's tones, but Balinese listeners were also sensitive to tonal relations in the slendro scale (Kessler et al., 1984). Moreover, cross-cultural research with the Tsimane', an indigeneous Amazonian people, shows that a preference for consonance and the sense of octave equivalence are not universal but rely on experience with particular musical systems (Jacoby et al., 2019; McDermott et al., 2016). So, although humans share certain perceptual and cognitive resources, these are inflected by cultural learning.

Like a computational model that is updated to better fit experimental data, listeners' musical expectations update to better fit the music around them. Through experience, they tune in to probabilities that define a musical style (Byros, 2012; Meyer, 1956). Tonal perception reflects the distribution of pitches in a key (Huron, 2006; Krumhansl, 1990), and even listeners without absolute pitch are sensitive to differences between keys (Eitan et al., 2017; see also Quinn & White, 2017). This does not require formal training and seems driven by statistical learning, a general way people pick up on regularities in complex stimuli. Statistical learning is relevant to many domains, including language, motor learning, and music (Perruchet & Pacton, 2006; Rohrmeier & Rebuschat, 2012). In music, listeners respond to the statistical regularities in melodic pitch structure in Western tonal music (Endress, 2010; Morgan et al., 2019; Pearce et al., 2010), North Indian rāgas (Rohrmeier & Widdess, 2017), and systems based on artificial musical scales (Loui, 2012; Loui & Wessel, 2008; Loui et al., 2010). Listeners also learn about probabilities in chord sequences (Huron, 2006; Jonaitis & Saffran, 2009; Loui et al., 2009). For example, at the end of every phrase in "Christus, der ist mein Leben," the dominant chord (V) resolves to the tonic (I). The sense of closure here relies in part on the ubiquity and predictability of that cadential formula. In the chorale's third phrase, Bach instead takes the dominant to the submediant (vi). In his chorale harmonizations, the V–vi progression is approximately fifty times less likely than V–I (Huron, 2006, p. 226; see also White & Quinn, 2018, p. 326), and it sounds more open-ended. Expectations for unfamiliar pieces, then, are shaped by prior experience.

This can be modeled via Bayesian methods, an approach to probability that balances current observations and prior beliefs (Temperley, 2007), and predictive processing theory, which offers a neurocomputational perspective on the interplay of top-down prediction and bottom-up sensory input (Clark, 2016; see also De Souza, 2020, sec. 3; Witek's chapter 7 in this volume). This theory distinguishes between uncertainty (no clear expectation) and surprise (expectation is not confirmed), and empirical research suggests that chord progressions are most pleasurable when they evoke low uncertainty with high surprise or high uncertainty with low surprise (Cheung et al., 2019). The dominant in the third phrase of Bach's chorale setting would engender low uncertainty, and the subsequent vi, relatively high surprise. According to predictive processing theory, this submediant should be especially salient for listeners, insofar as it is an unpredicted input that follows a relatively confident (but unsuccessful) prediction.

Each listener, however, can have different sets of expectations. Certain chords, such as the subtonic (♭VII), or harmonic progressions are rare in baroque music but common in rock. One computational study compared Bach's chorale settings and songs from *Billboard*'s "Hot 100" list, arguing that these repertoires have different tonal functions (White & Quinn, 2018). Accordingly, listeners prefer V–I over ♭VII–I in a classical context, but they find the latter acceptable in rock (Vuvan & Hughes, 2019). Similarly, studies of bimusicality have investigated listeners who are enculturated to more than one musical system (e.g., Western and Indian classical music; Wong et al., 2011). The ability to switch ears might seem to be attributable to contemporary technology and cultural exchange, to a world where listeners have access to diverse recordings and music from distant times and places. Yet arguably, Bach and his contemporaries already had multiple sets of expectations: the composer wrote several organ preludes based on modal chorale tunes, which can sound unresolved to listeners who are not familiar with seventeenth-century modal "church keys" (Barnett, 1998; Fitzpatrick, 2015). For example, "Nun komm, der Heiden Heiland" ends on the final of the A Dorian mode, which can easily be mistaken for the dominant of D minor (figure 6.2). So, tonal perception responds to statistical regularities but is also sensitive to context.

There is no single, universal harmonic syntax, then. Similarly, some cognitive linguists criticize Chomsky's universal grammar, highlighting the structural diversity of human languages. In this view, "language is a bio-cultural hybrid, a product of intensive gene-culture coevolution" (Evans & Levinson, 2009, p. 431; on gene-culture coevolution and music, see Patel's chapter 1 in this volume). Some argue, somewhat controversially, that syntactic recursion is not available in languages such as the Amazonian language Pirahã (Everett, 2005). This represents a different approach to language and mind.

Nonhierarchical linguistics have also been applied to music. Instead of focusing on discrete words (arranged according to meaning-neutral grammatical rules), construction

Figure 6.2
Bach's "Nun komm, der Heiden Heiland," BWV 599, mm. 9–10

grammar highlights extended linguistic units involving conventional pairing of syntax and semantics, form and function (Goldberg, 2006). Construction grammar–inspired approaches offer a different interpretation of the harmonic phenomena discussed earlier (Gjerdingen & Bourne, 2015; Zbikowski, 2017). In this view, listeners are not simply attuned to the distribution of individual notes or chords. Instead, they learn larger schemas, and a cadence is more meaningful than the parts that constitute it. Cadences involve processes in multiple syntactic layers (e.g., harmony, melody, rhythm), and this syntactic organization is tied to their meaning or function (providing a sense of closure). A listening mind, then, would not parse the music chord by chord, like a novice theory student working through a roman-numeral analysis. Instead, it might resemble a student at an eighteenth-century Italian conservatory, where pupils learned how to recognize, improvise, and compose with stock contrapuntal patterns (Gjerdingen, 2007). Bach's teaching was similar: it did not define a set of chords and rules for arranging them in functional progressions; instead, his students harmonized chorale melodies at the keyboard (Leaver & Remeš, 2018). Their training focused on constructions, on meaningful musical utterances.

While debates about musical grammar continue, it seems clear that music has often been considered cognitive insofar as it resembles language. Linguistic comparisons have shaped understanding of the musical mind, partially because language has long been considered the essence of thought. Certainly, language and music are both distinctively human cognitive phenomena, and they are processed in similar ways (Patel, 2003; Koelsch et al., 2005). And computational, statistical, or probabilistic approaches have much to offer interdisciplinary research on music cognition: they can help clarify links between musical organization and listeners' responses, especially when they account for individual and cultural learning. Yet these approaches often present music as text more than performance, as abstract idea more than embodied practice, excluding motion, dance, and other modes of physical engagement. To quote Suzanne Cusick (1994, p. 16), they treat music as a "*mind–mind* game," an art that is produced by one mind and received by other minds. But musicians and listeners are neither disembodied spirits nor sophisticated robots; they are living, breathing, feeling organisms who move and are moved, who feel pleasure and pain. And this, too, has implications for the musical mind.

Musical Minds, Musical Bodies

How are mind and body related? According to various forms of dualism, mind and body are more or less separate. This thinking is often attributed to the early modern philosopher René Descartes, though it has older roots. In a sixth-century treatise that was influential throughout medieval Europe, the late-Roman polymath Boethius argues that music theory is nobler than performance, just "as the mind is superior to the body" (1989, p. 50). Boethius, Descartes, or twentieth-century computationalists do not deny that humans have bodies. But many see the body as an auxiliary to cognition, not an active participant in it. In this view, the body provides sensory input to the mind and receives its commands, but the body itself does not think or speak or listen. As Descartes wrote, "it is the mind which senses, not the body" (2001, p. 87).

Does the body contribute to music cognition, then? Leonard Meyer considered this problem in the 1950s:

> On the one hand, it seems clear that almost all motor behavior is basically a product of mental activity rather than a kind of direct response made to the stimulus as such. . . . On the other hand, the facts indicate that somehow motor behavior does play an important part in facilitating and enforcing the musical aesthetic experience. (1956, p. 81)

Meyer argues that all motor activity corresponds to mental activity—but that mental activity, by contrast, is not reducible to motor activity. As such, he concludes that bodies do not require a separate analysis, despite their experiential significance, and "music is best examined in terms of mental behavior" (Meyer, 1956, p. 82). This conclusion has clear Cartesian implications. Meyer even quotes a line that paraphrases Descartes (from the French musicologist, pianist, and philosopher Gisèle Brelet): "Rhythm comes from the mind not the body" (quoted in Meyer, 1956, p. 81).

Yet consider a series of experiments by Jessica Phillips-Silver and Laurel Trainor (2005, 2007). Participants heard metrically ambiguous rhythmic patterns and bounced on every second or third beat. Later, they heard versions of the rhythmic pattern with accented strong beats in duple or triple meter. Infant participants chose to listen for a longer time to the accented version that matched their earlier movement, and adults matched the accented pattern to their bouncing pattern. Bodily movement was essential for this effect: it persisted when participants were blindfolded but not when they watched someone else bouncing. In this case, bodily movement influences rhythm perception, and listeners hear what the body feels. Moreover, beat perception involves brain regions that are implicated in motor activity, including the basal ganglia, premotor cortex, and supplementary motor area (Cannon & Patel, 2021; Grahn, 2009). Brain regions do have multiple functions (Anderson, 2014), and this does not mean that the experience of meter always requires bodily movement. Still, moving to music can affect metric perception, much as gesturing affects reasoning and problem solving (see Alibali et al., 2011; Goldin-Meadow & Beilock, 2010). So, despite Meyer's efforts, it is not easy to explain away bodily aspects of music perception and cognition.

The dualism that drives Meyer's dilemma is a theoretical commitment. It is not directly testable. Searching for a clean boundary between mind and body—or entirely rejecting the mind-body distinction—seems unproductive. Arguably, it is better to accept continuities between minds and bodies and ways in which they are intertwined without being identical (see De Souza, 2017, pp. 11–12). This approach can draw on established frameworks from phenomenology (Merleau-Ponty, 2012; Montague, 2011), embodied cognitive linguistics (Lakoff & Johnson, 1980; Johnson, 1987), or biology (Maturana & Varela, 1980). From the latter perspective, life itself is fundamentally cognitive: when a single-celled organism seeks nourishment or a plant turns its leaves toward sunlight, it is already engaged in a process of sense making; even though these organisms are not conscious, their behavior can be understood as a precursor to human cognition. This would expand the definition of mind and resolve Meyer's opposition by framing motor activity as a particular kind of cognitive activity.

Admittedly, this conceptual shift can be a source of controversy. Some proponents of embodied cognition reject tenets of standard cognitive science, such as computation and mental representation. However, these viewpoints can also be combined. Some cognitive scientists would accept the physical and neural foundations of computation (Shapiro, 2011, sec. 1.3) or reinterpret earlier findings in embodied terms, so that the benefits of computational research are not lost (Barsalou, 2010). Where standard cognitive science might view cognition as computation with abstract, amodal symbols, a more embodied paradigm would emphasize perceptual symbols grounded in the brain's systems for sensation, perception, and action (Barsalou, 1999, 2008). It can also open up new avenues for empirical research, including tasks with bodily movement or action, and data collection involving motion capture, physiological measures (e.g., heart rate), and so forth. And because the body has long been a topic of inquiry in musicology, phenomenology, anthropology, and related fields, cross-disciplinary research can investigate shared concerns: for example, certain phenomenological concepts related to embodiment have been operationalized and tested experimentally (Dotov et al., 2010; Maravita & Iriki, 2004). As such, an embodied viewpoint can facilitate collaboration between cognitive science and the humanities.

Rhythm offers clear examples of embodied music cognition, partially because physical movement and sound can share the same temporal patterning. Yet theories of embodied cognition also address aspects of pitch perception. In the West, pitch space is typically imagined in terms of vertical position. For example, the second melodic note in “Christus, der ist mein Leben” is “higher” than the preceding pickup, and in the chorale’s first measure, Bach’s bass line steadily “descends.” This terminology matches visual aspects of the music notation, but obviously no literal, physical ascent or descent occurs here. These pitch changes instead involve variations in the sounds’ frequency. Nonetheless, this understanding of pitch height affects perception. In representative experiments, audiovisual stimuli were presented to participants with and without formal musical training. When higher pitches were paired with higher visual stimuli, their responses were faster and more accurate (Lidji et al., 2007; Rusconi et al., 2006).

To explain such phenomena, music theorists have again taken inspiration from cognitive linguistics, suggesting that conceptualization of pitch height involves what Mark Johnson (1987) calls “image schemas” (see Brower, 1997; Cox, 2016, ch. 4; Johnson & Larson, 2003; Mead, 1999; Zbikowski, 2002). Image schemas are gestalts abstracted from sensorimotor perception (Rohrer, 2005), which can ground conceptual metaphors (Lakoff & Johnson, 1980). The verticality schema, derived from countless experiences of up-and-downness, supports conceptual metaphors ascribing locations to musical pitches, emotional states (in statements such as “Cheer up” or “I’m feeling down”), or even religious entities (e.g., God and Heaven above, Hell below). In music, this can support the sense of tonal “gravity” (Larson, 2012)—as in the end of “Christus, der ist mein Leben,” where the melody steps down and comes to rest on the tonic. It can also support musical imagery—as in Bach’s organ prelude “Durch Adams Fall,” where dissonant descending leaps represent a spiritual fall from grace.

Once again, this is not universal but learned. Across cultures, pitch is mapped onto many different domains (Eitan & Timmers, 2010). For example, Javanese musicians describe pitch relationships in terms of tension and size: pitches are not low or high but loose or tight, big or small (Zanten, 1986, p. 85). Though they do not rely on verticality, these theoretical metaphors also relate music to sensorimotor experience. When Lerdahl and Krumhansl discuss tonal “tension,” they draw on the same tension metaphor as Javanese theory: “Everyone experiences physical tension and relaxation,” they note, “and it is common to extend the terms to mental and emotional terrains as well" (2007, p. 330). Image schema–based conceptual metaphors are common in various kinds of music theory (Saslaw, 1996; Zbikowski, 2002). Language for discussing and thinking about music builds on other areas, including bodily experience.

Listening to music does not involve only metaphorical movement. Foot tapping, dancing, head bobbing, and other movements often emerge spontaneously. They reflect embodied ways of engaging with the music (Kozak, 2015; Witek, 2017). When music evokes a desire to move, it is said to have high "groove" (Janata et al., 2012), and this pleasurable sensation involves motor and reward networks in the brain (Matthews et al., 2020). Although groove is related to moderate rhythmic complexity (particularly syncopation), it can also be affected by pitch. One study found that moderate harmonic complexity, combined with moderate rhythmic complexity, enhanced musical pleasure and the impulse to move (Matthews et al., 2019). Other experiments suggest registral differences: stronger bass parts contribute to groove (Stupacher et al., 2016), and when these low frequencies could be *felt* as well as heard, participants gave higher ratings of groove and aesthetic pleasure and displayed more spontaneous movement (Hove et al., 2020). This involves a multisensory experience of music, combining auditory and tactile stimulation.

That said, music's effects on the body are as varied as human bodies themselves. Drawing on disability studies, Joseph Straus critiqued embodied music theory for "the blithe assumption that we all inhabit the same kind of body, a normatively abled body, and thus all experience our bodies in pretty much the same way" (2006, p. 123). For example, tactile and visual aspects may be particularly central for musicians with impaired hearing, such as percussionist Evelyn Glennie or members of the deaf rock band Beethoven's Nightmare—although as Jessica Holmes (2017) discusses, deaf listening and deaf musicality are diverse and often misunderstood. Such research emphasizes that disability is cultural as well as biological, and it demonstrates the importance of individual and group differences.

Performance expertise points to another set of bodily differences in which action and perception are combined. For singers, tension is not simply metaphorical: vocal tension and muscular tension are palpable. Instrumentalists cultivate bodily skills that require an external tool, modes of music cognition that are impossible without technical mediation. For pianists, pitch space goes from left to right as well as from low to high, and this is reflected in their responses in the aforementioned experiments (Lidji et al., 2007; Rusconi et al., 2006). Their model of pitch space has been shaped by the technical interface of the keyboard. So, merely including the body in cognition does not go far enough. If embodied cognition involves learning, with cultural and individual differences, the mind-body is not fixed but dynamic; it is situated in and conditioned by the world. Our purview must expand to reveal the mind-body interacting with objects and others.

Music, Mind, and World

Every mind requires a body that supports it, and likewise, every body is situated in a world. This is central to ecological psychology, founded by James J. Gibson (1966, 1979a), which emphasizes that perception always involves an organism in an environment. And as Gibson notes, tools can complicate the boundary that separates them:

> When in use, a tool is a sort of extension of the hand, almost an attachment to it or a part of the user's own body, and thus is no longer a part of the environment of the user. . . . This capacity to attach something to the body suggests that the boundary between the animal and the environment is not fixed at the surface of the skin but can shift. (1979a, 41; see also Maravita & Iriki, 2004)

Tool use is fundamentally relational, involving an interaction between agent and object. The object has certain affordances (i.e., possibilities for action), but these are available only to an organism with appropriate abilities (Gibson, 1979b). For example, apples can be eaten by many animals and can be thrown by many humans (though not by horses), but apples can be juggled only by practiced performers. Similarly, musical instruments are playable in a general sense—after all, toddlers and professionals alike can press piano keys—but more affordances become available with training. And as new skills open up possibilities for action, they also change what is perceptible to the organism (Dreyfus, 2002).

As I argued in my book *Music at Hand*, learning to play an instrument affects players' perception, cognition, and imagination (De Souza, 2017). The instrument consistently converts action into sound. With practice, this establishes a two-way auditory-motor connection in a player's brain (Bangert et al., 2006; Chen et al., 2011; Drost et al., 2005; Lahav et al., 2005; Margulis et al., 2009). I describe this as a link between the hand and the ear. The auditory-motor coactivation can be stimulated in various ways: when instrumentalists listen to music they can play, there is corresponding activity in the primary motor cortex, even though they are not moving (Haueisen & Knösche, 2001); when they move their fingers to virtually play in the absence of the instrument, there is activation in the primary auditory cortex (Lotze et al., 2003). Just imagining the performance does not evoke this coactivation. Similarly, the auditory-motor coupling never emerges when beginners practice on a keyboard where the pitch-to-key mapping is random and changeable (Bangert & Altenmüller, 2003). This indicates that the instrument's stable affordances are essential for this distinctive form of multimodal integration.

Because this training responds to the instrumental interface, different kinds of instrumentalists tend to have particular ways of imagining and experiencing musical space. For example, keyboard instruments set up an opposition between the white notes' C-major scale and the sharp or flat black notes. This structure seems to influence many musicians with absolute pitch, who respond more quickly and accurately to white notes (Miyazaki, 1988, 1990). Pitch labeling is also more accurate with notes with piano timbre, relative to sine tones (Reis et al., 2021), and some musicians may have a form of instrument-specific absolute pitch (Reymore & Hansen, 2020; see also Hedger et al., 2013). Instrumental features can also ground musicians' theoretical models: for example, the big-small pitch mapping in Java, mentioned earlier, corresponds to the size of metal bars in tuned percussion instruments that are central to gamelan ensembles. In such cases, the instrument serves as a cognitive reference point.

Performance experience also varies with different instruments. The organ's multikeyboard interface—with manuals, pedals, and stops—offers a particular kind of embodied thinking. The instrument allows for textures where three independent lines are realized on three different keyboards—two for the hands and one for the feet. As the organist and musicologist David Yearsley writes, "Anyone who has played a trio at the organ . . . knows what thinking this way feels like in the body" (2012, p. 50). At the same time, anyone who has never played the organ does *not* know how this feels. The organist's knowledge is not only declarative but also procedural, a kind of know-how.

Instrumental interfaces can shape distinctive idioms. For example, pedal points (long, held bass notes) are facilitated by the organ's capacity for endless sustain and its powerful low register (De Souza, 2017, p. 40). Yet there are also aspects of performance that are felt by performers but not directly heard by listeners. Cusick illustrates this by describing a physically challenging moment in Bach's chorale prelude on "Aus tiefer Not" (figure 6.3):

> Neither foot can rest long enough to balance the body, neither hand can rest long enough to balance the body. For these few terrifying measures (terrifying in the organist's experience), one might as well be floating in mid-air, so confused and constantly shifting is the body's center of gravity. (1994, p. 18)

This physical imbalance corresponds to the absence of grace in the chorale's lyrics, and balance is regained at the arrow in the figure, when grace arrives in the text.

When Bach's students realized chorale tunes at the keyboard, they used body-instrument interaction to create and think about harmony. Seemingly abstract voice-leading rules can take on a physical character here: for example, moving the hands in contrary motion is a performance strategy that often avoids parallel fifths and octaves.

Figure 6.3

Bach's "Aus tiefer Not," BWV 686 (Cusick, 1994, fig. 2). The arrow indicates where the performer's body (hands playing the upper two staves, feet playing the bottom stave) returns to a state of balance.

In a sense, the students' knowledge of tonal syntax involved both the instrument and their hands (Bianco et al., 2016; Sammler et al., 2013). An experiment by Giacomo Novembre and Peter Keller (2011) illustrates this well. Pianists imitated silent videos that showed one hand playing chord progressions on a keyboard. Imitation was fastest when a chord fit the established harmonic context, which suggests that the videos supported both tonal and physical expectations. Additionally, imitation was less accurate when a harmonically conventional chord was performed with unconventional fingering. Overall, this suggests that for expert instrumentalists, musical syntax may involve an embodied "grammar of action" (Novembre & Keller, 2011).

Musical instruments, then, can complicate the boundary between mind-body and world, and theorists of cognitive extension would argue that such objects become part of the mind. This is not to say that a pipe organ can think; rather, it can serve as a functional component in a larger cognitive system (Clark, 2008). It is possible to harmonize a chorale melody, solve a math problem, or remember a set of directions in one's head—and these are undeniably cognitive. According to the extended mind hypothesis, these routines remain cognitive when they incorporate external objects such as a keyboard, calculator, or notebook. In any case, the instrument does make it possible to off-load certain aspects of the task. For example, the organ takes care of tuning, and it provides the energy that sustains the pitches. Such contributions are implicated in a comment on performance attributed to Bach by Johann Friedrich Köhler in 1776: "All one has to do is hit the right notes at the right time, and the instrument plays itself" (quoted in Marshall, 1999, p. 93).

Of course, body-instrument interaction occurs in a social context too. Bach's students watched and listened to him play, and imitation remains central to music lessons today. Neuroscientific studies have explored imitation in guitar learning, emphasizing how the brain's action observation network is engaged while watching a teacher and also when reproducing chords (Buccino et al., 2004; Gardner et al., 2017; see also Rizzolatti & Sinigaglia, 2008). This interpersonal coordination is also essential for ensemble performance, and it might be especially prominent in collective improvisation (as in the Balinese genres discussed by Tilley, 2019). For music theorist Arnie Cox, bodily imitation is important for audiences too. According to his mimetic hypothesis, listeners make sense of music by overtly or covertly imitating performers' actions and the sonic patterns they create (Cox, 2011, 2016). Interaction with others, then, would be central to music cognition.

Indeed, music supports social bonding across multiple human cultures (Savage et al., 2021). For example, choral singing increases participants' trust, cooperation, and feelings of closeness (Anshel & Kipper, 1988; Weinstein et al., 2016). It is possible that this kind of participatory music making affects neurochemistry, increasing oxytocin or reducing cortisol, although current results are inconclusive (Bullack et al., 2018; Chanda & Levitin, 2013; Keeler et al., 2015; Kreutz, 2014; Schladt et al., 2017). With religious ritual, dance, or collective work, this is one of music's central affordances: it facilitates the coordination of minds and bodies (Clarke, 2005; Kozak, 2019).

Emotion is also central to music's "social affordances" (Krueger, 2011a). Music can support emotional contagion, and it can be understood to represent a "super-expressive voice" (Juslin & Västfjäll, 2008). Empirical studies confirm parallels between acoustic cues for emotion in music and speech: both tend to sound "happier" when they are higher, faster, and louder (for a review, see Schutz, 2017). This points to the significance of register, an aspect of pitch that is often neglected by Western music theory focused on pitch class. Of course, musical simulations of emotional processes typically combine multiple syntactic layers, as Lawrence Zbikowski (2017, pp. 10–11, 79–91) demonstrates in an analysis of Bach's cantata *Ich habe genug*. If music functions as a kind of virtual other, then music cognition would overlap with aspects of social cognition (Wallmark et al., 2018). In music and other domains, the extended mind might include others as well as objects (Krueger, 2011b), with cognitive processes that integrate multiple minds and bodies.

Ultimately, the mind, as revealed in music, involves multiple levels—from mental computation to embodied action to cognitive extension. These interrelated levels can be studied on their own or in various blends. Each one mixes nature and culture, so each benefits from a combination of scientific and humanistic methods. Multiple disciplinary perspectives are needed, then, to understand musical minds, bodies, and worlds.

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