The Science-Music Borderlands

Reckoning with the Past and Imagining the Future

Edited by: Elizabeth H. Margulis, Psyche Loui, Deirdre Loughridge

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13 Composing at the Border of Experimental Music and Music Experiment

Grace Leslie

Music cognition and experimental music are practices that emerge from separate disciplines yet share several overarching goals. Their creators use the same algorithms and hardware to generate stimuli or compositions. These compositions often use the simplest building blocks of sound: sine waves, clicks, and pulses. Such stimuli probe singular facets of human auditory perception and music experience and force the listener to encounter the fallible machinery that makes the act of listening possible. Using shared tools, music cognition researchers and composers have explored the same terrain for decades. Karlheinz Stockhausen, a pioneer of electronic music in postwar Germany, wrote of the need to blur the boundaries between the two disciplines to bring electronic music practice into a new era: "The musician, therefore, for whom the question of research in sound had for the first time become acute, has been obliged to undertake a considerable amount of this research himself. He has had to expand his métier, and to study acoustics, in order to better the acquaintance with his material" (Eimert & Stockhausen, 1959, p. 60).

Electronic and computer music techniques enable the exploration of perception through sculpting of sound in its time and frequency domains to match our engineering preferences, bypassing the limitations of acoustic instruments and concert halls. Our music and sound perception, whether through evolution or experience, expects sounds to have certain spectral shapes due to the physical characteristics of resonant bodies (Theunissen & Elie, 2014)—but we can circumvent these expectations by engineering acoustic patterns directly.

I compose this circumventory music as an auditory-music experiment, inspired by two parallel research paths. The field of music perception and cognition is tasked with mapping and understanding the roles that various perceptual mechanisms and anatomies play in perceiving, understanding, remembering, and responding to music. It's a composer's thought experiment to wonder how one might create music for the express purpose of driving the perceptual mechanism and physiology in a particular way, let alone how to use this engineered music as a means to benefit the listener.

Here, I present a part of my musical work that exists at this borderland between experimental music and music experiment. I first acknowledge the scientist-composers whose work established the conceptual framework on which I build. These are examples in which control and exploration of the perceptual mechanism are the goals: a composer creates a piece with the goal of probing the inner workings of the mind, and a scientist creates a stimulus to map the brain's response to sound.

Music cognition researchers often electronically generate or manipulate auditory stimuli to elicit particular perceptual experiences, with the goal of explaining one or more specific aspects of music cognition; however, in focusing on these methods, I do not mean to imply that they are employed only in this field. As explored by Williams and Sachs (see chapter 11 in this volume), other strains of music cognition research use naturalistic paradigms that attempt to re-create everyday music listening experiences for each participant, aligning with the earlier Gestalt positioning of complex experience as more than the sum of its simplest components.

Max Mathews's (1963) 1957 MUSIC I program was the first to perform musical tones and compositions with a digital computer. Roger Shepard (1964) was among the first to use computer-generated musical tones to demonstrate aspects of music perception and cognition, in his case, the circular nature of relative pitch discrimination. Diana Deutsch (see chapter 14 in this volume) has composed many musical illusions and paradoxes that reveal individual differences in the perception of musical patterns. In her octave illusion, the right and left channels of a stereo composition each contain a sequence of two alternating tones spaced one octave apart (Deutsch, 1981). The two sequences are arranged such that the higher tone is played in one channel when the lower tone is played in the other channel. Although the stimulus is a two-tone chord, with the ear of presentation switching with each repetition, the perception of this stimulus varies among listeners. Some always hear the high tone in the same ear, often corresponding to their handedness, while other listeners exhibit even more complex illusions. Deutsch conjectured that this ambiguity arises from two competing mechanisms attempting to form a combined percept—one responsible for pitch perception, and the other responsible for location perception. In the presence of these two contradictory streams of information, we end up suppressing the pitch perception of one stream in order to weave together a more probable explanation. The scale illusion (Deutsch, 1974) operates on a similar conjunction of pitch and location. Because it is much more likely for a single musical source to play with stepwise motion in a fixed location, we perceive this arrangement of pitch and location rather than the correct but improbable interpretation. Jean-Claude Risset (1978, 1985) created similar illusions and incorporated them into his electroacoustic compositions.

In Iannis Xenakis's electronic music compositions, huge masses of sound are created by specifying the statistical trends of randomly generated sound features over the course of a piece, rather than individually generating and controlling musical voices (Xenakis, 1992). *Concrete Ph* is an exemplar of this approach: a tape composition intended to evoke a large "cloud" of sound (Bridoux-Michel & Xenakis, 2005). *Concrete Ph* was written as an interlude during the premiere of Varése's *Poeme electronique* at the 1958 World's Fair in Brussels (Treib & Felciano, 1996). Xenakis's approach to *Concrete Ph* involved splicing, looping, mixing, and speed-changing one-second fragments of recordings of burning wood (Roads, 2004). These small pieces of sound were layered to such a degree that a singular cloud-like sound mass resulted from the mix. Xenakis wrote of his intuitive approach: "Start with a sound made up of many particles, then see how you can make it change imperceptibly, growing and developing, until an entirely new sound results" (Brody, 1970). However, the final composition was written for eleven channels and diffused over the loudspeaker system at the fair's Philips Pavilion, creating a blurry distinction between individual sound "grains" and the composite "cloud," thus becoming an informal experiment in spatial audio perception. With greater distance between channels, the human auditory system is better able to distinguish between multiple sound sources (Blauert, 1997). Thus, we travel along a "phase state" curve between the sound cloud and the many separate voices (Schick, 2007). It can only be imagined that as spectators walked around in the space, their changing locations allowed them to travel along this "phase state" curve, experiencing the fragile boundary between sound fragments and clouds and thus experimenting with the limits of their own auditory perception. Xenakis used this technique in many of his percussion compositions, such as *Persephassa* and *Rebonds*; however, the flexibility of the diffused electroacoustic medium allowed him the fine-grained control to experiment with the smooth transition between these varying states.

Fred Lerdahl famously straddled the composition-research divide with his (and Jackendoff's) generative theory of tonal music. His practice as a composer led to key research insights to shift music-generating algorithms toward outputs relevant to the internal mental representations created by the listener. For instance, he proposed that composers of contemporary serial music who adopt artificial grammars do so in violation of the intuitive constraints that govern the music listening process (Lerdahl, 1992).

These researchers and composers wrote compositions to probe the inner workings of the musical and auditory mind, and my recent compositions attempt something similar: they are engineered to play the brain and the body as an instrument. These tracks are algorithmically generated and designed to be played continuously at low volume throughout the listener's day, creating an ambient presence in the surroundings and subtly shifting the body by inviting a parallel internal entrainment through the auditory perceptual mechanism and autonomic nervous system.

These works contain computer-generated tones employed as tuning forks to find the sympathetic resonances in the body's rhythmic functions: brain dynamics, respiration, heartbeat. Neuroscientists and doctors have developed stimulation protocols using electricity and magnetism to noninvasively produce rhythmic brain patterns to target particular wavelengths, frequencies, and anatomy. This line of research echoes medical practices from centuries ago built on the belief that the nervous system can resonate sympathetically with external vibratory stimuli (see Raz's chapter 5 in this volume). More recently, this concept has been extended to sensory neurostimulation: the use of sensory stimulation—light and sound—to create sympathetic rhythms in the brain and nervous system (Adaikkan & Tsai, 2019).

My performance practice is the result of years of "n = 1" experiments in which I discovered which kinds of flute playing and breathing affected my physiology to the extent that I could incorporate my own body signals into live electronic music compositions. I present these concepts along with a record of scientific experiments my colleagues and I have undertaken during my time at MIT, Dartmouth, and Georgia Tech. Taken together, these results are a first validation of this brain-body music concept.

Breathing Music

Breathing is a unique autonomic function, in that it is simultaneously consciously and unconsciously controlled. In this way, it can act as a gateway for the conscious manipulation of the autonomic state. Music has been written with the express purpose of training listeners to regulate their breathing patterns (Bernardi et al., 2006; Siwiak et al., 2009), inducing relaxation (Yu et al., 2018) and meditative states (Vidyarthi & Riecke, 2014), reducing muscle tension (Robb, 2000), and influencing both electrodermal activity and heart rate variability (Bhandari et al., 2015). This intentional control of breathing may regulate deeper autonomic states, and although breathing remains under autonomic control, we can override this control through our own efforts or environmental influences (Moraveji et al., 2011).

In my own performances, I find that the way I breathe has a profound effect on the composition, triggering a cascade of changes in other physiological signals (e.g., heart rate and electrodermal activity) that I record using sensors. Breathing itself is translated into sound when I play long tones into the flute, one tone per breath, or when

I amplify the sound from a stethoscope placed on my chest. The underlying tempo of this pattern is reinforced by looping algorithms that synchronize with this rate.

In 2017, at the MIT Media Lab under the auspices of Rosalind Picard's Affective Computing Group, my colleague Asma Ghandeharioun and I created an experiment to test whether an ambient music track designed to mimic the time course of relaxed breathing could invite listeners to change their own breathing to match the track (Leslie et al., 2019). I composed an algorithmically generated musical composition that breathed softly along with the listener, either according to a predetermined "ideal" breathing rate or in response to data streamed online from a respiration sensor worn by the listener. During the experiment, we did not inform listeners that the mass of tones surrounding them were mimicking their own fluctuations of breath or were designed to influence their breathing. The listeners were given an unrelated reaction-time task and told that the music was being provided to prevent boredom. We recorded the respiration trace, electrocardiogram (ECG), electroencephalogram (EEG, to measure brain waves), and electrodermal activity (EDA) of listeners as they experienced this subtle breathing presence in the room. We found that listeners' breathing rates slowed to match the musical ambience, and their other autonomic functions followed suit, indicating a general relaxation response. The EEG data showed an impact on the contingent negative variation (CNV) measured between the warning and imperative stimuli during the reaction-time task they completed, indicating that slower breathing influenced the level of cortical arousal in the brain elicited by this task. Interestingly, the music was most effective at slowing breathing when the tempo was fixed at a rate slightly slower than each listener's natural breathing rate, suggesting an added benefit to personalizing the music based on the listener's body signal information. Given that we did not instruct the listeners to match their breathing to the music, we concluded that some part of the sympathetic slowing was due to the unconscious influence of the music. As a performer, I continue to use this technique with the intention of creating synchrony, broadly defined, with an audience.

Brain Music

I have performed for several years using my EEG signals by applying a sonification algorithm that imprints their spectral quality onto a bank of stored flute and voice sounds, which I mix with my own live flute improvisation (Leslie, 2021). This performance practice emerged from an exploration of various breathing control methods intended to both create changes in the sonified sound and initiate a cascade of body and brain events. The nature of the musical composition itself played a role in my ability to sustain attention for the time required to create an expressive arc with this method: my long practice sessions formed a singular open composition. The slow and diatonic qualities of the music fed back into my mental state, making it possible to sustain the performance. After I began to perform this piece publicly, audience members reported that they found it very relaxing, indicating that some sympathetic process was at work. I began to imagine this performance practice as a sharing of a particular brain and body state that the sonified sound helped communicate to my audience. I took this idea of sympathetic response one step further by producing a series of music tracks designed to stimulate the brain within the EEG spectrum to produce beneficial effects.

There are precedents for this idea in medicine and medical research, specifically for the treatment of epilepsy and other neurological disorders. Epilepsy is characterized by an intense regularity emerging from networks of neurons firing synchronously in the brain (Duncan et al., 2006). Over time, this intermittent synchrony results in channels where these streams of voltage run through the brain, damaging memory and cognition. Doctors have discovered that inserting a competing, regular electrical pulse into this network can interrupt this synchrony and prevent a seizure (Schulze-Bonhage, 2017). Vagus nerve stimulation protocols (Ben-Menachem, 2002) are preprogrammed for the patient, creating an open-loop system (González et al., 2019). In contrast, responsive neurostimulation is engineered as a closed-loop system, in that it continuously monitors brain activity for signs of epileptiform activity and automatically introduces targeted brain stimulation at the site of seizure generation in the brain (Morrell, 2011; Sun et al., 2008). Thalamic stimulation also has anticonvulsive effects (Fisher et al., 2010). While the mechanism of action remains to be explained (Vonck et al., 2001), these therapeutic protocols are thought to promote plasticity and desynchronize cortical rhythms contributing to epileptiform activity (Sohal & Sun, 2011). Multiple stimulation protocols using various waveforms have been compared, including DC stimulation, single pulses, phase resetting, and low- or high-frequency periodic stimulation (Durand & Bikson, 2001; Schiller & Bankirer, 2007).

Scientists are also developing sensory neurostimulation protocols using flickering light and pulsatile audio stimuli to evoke oscillations at specific frequency bands. Gamma-band oscillations induced with flickering lights reduced signs of Alzheimer's pathology in mouse models (Martorell et al., 2019), and similar work in the audio domain is under way. While a postdoctoral fellow at Dartmouth in 2017, I proposed a musical sensory neurostimulation protocol inspired by this work. I produced musical samples containing low-frequency acoustic energy that overlapped the spectrum of gamma-band neural activity and played these to postoperative brain surgery patients at Dartmouth-Hitchcock Medical Center. Dr. Barbara Jobst, Robert Quon, and others in the Epilepsy and Cognition Lab have conducted further experiments using these musical neurostimulation stimuli (Quon et al., 2021). By analyzing the electrocorticography (ECoG) data of these patients as they listened to the stimuli, we found that these tones reduced interictal epileptiform activity in patients who normally demonstrated high levels of this indicator. I have incorporated similar low-frequency acoustic tones in electronic compositions such as *Sonic Tonic* (2014) and *Fais de moi un instrument* (2021). Although the technique is far from being adopted by the medical community, the results of the experiment may ground the neurostimulation metaphor developed first in my performance practice and then in my electronic compositions.

Heart Music

Of all the body signals I've incorporated into my brain-body music performance practice, directly amplifying the heart using a microphone placed inside a stethoscope tube has had the most direct effect on my listeners. During one listening session in Tokyo in 2015, I asked the audience to write down what thoughts the performance evoked for them. One audience member recalled being in his mother's womb; another described seeing a spiritual teacher returned to life. This performance technique mimics the body's own interoceptive awareness. By playing my own heartbeat onstage, I create an experience that gives listeners the sense that they are inhabiting my body, as they hear my heartbeats as their own.

For his PhD dissertation at Georgia Tech, Mike Winters (2020) studied how listening to heartbeats affected empathic states. He played synthesized heartbeat sounds to subjects as he recorded their ECGs and EEGs. He also tested their empathic reactions to this listening exercise. He found that listeners' heartbeats slowed to match the heartbeats of the imaginary person they were hearing, and this process of listening to heartbeats caused them to shift their empathic reactions to expressive faces (Winters et al., 2021). Most interestingly, his analysis of the heartbeat evoked potential (HEP) revealed a difference between most empathic and less empathic trials: the intensity of the HEP curve decreased with greater empathy, suggesting fewer neural resources supporting interoception, or the awareness of one's own heartbeat (Winters, 2020). Winters's research suggests several avenues by which heartbeats can be used to invite and sustain empathic reactions between individuals.

This result also leads to a question: can the unconscious transfer of body awareness from oneself to another through the imitation of bodily functions at least partially explain how music arouses emotional responses? Juslin (2019) lists thirteen different mechanisms by which emotion may be elicited in music listeners. The effect examined here could be categorized as both "rhythmic entrainment" and "contagion." However, results suggest that interoception may be an underlying brain-body mechanism that supports both modes of emotional arousal.

In all three examples—breathing, brain, and heart music—both formal experiments and informal experimental music reached similar conclusions, supporting the idea that sympathetic shifts in physiological oscillations may play a role in the listener's musical experience. Both approaches have their limitations. In the case of our scientific experiments, the stimuli are too simple to be considered "music" by most listeners. In fact, in the epilepsy experiments, several patients found the low-frequency acoustic stimuli unpleasant to listen to. Conversely, my informal compositional experiments lack the experimental controls necessary to extend these results to a broader theory or conjecture about music perception. These performances contain stimuli that are too naturalistic and complicated to properly tease out the effects of individual acoustic features. Important work is being done to develop formal yet naturalistic experiments to study the neural and body dynamics supporting live music performance, such as the recent experiments undertaken at the LiveLAB at McMaster University (Dotov et al., 2021).

In this chapter I've attempted to map the borderland between music experiments and experimental music. There are important historical precedents in both fields, and current work owes much to the scientists and composers who designed these initial experiments. It is also important to acknowledge the institutional support that made the work of these composer-researchers possible. In addition to the previously mentioned universities and research centers that supported the works described in this chapter, others such as the Institut de Recherche et Coordination Acoustique/Musique in Paris, the Center for Interdisciplinary Research in Music Media and Technology in Montreal, and the Max Planck Institute for Empirical Aesthetics continue to support scientists and artists working in these borderlands.

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