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Polyrhythmic Pathways: Using Bimanual Coordination Research to Develop a New Framework for Practice, Performance, and Pedagogy

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Christian Swafford, Student

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Dr. Lance Brunner, Director of Graduate Studies

POLYRHYTHMIC PATHWAYS: USING BIMANUAL COORDINATION RESEARCH TO DEVELOP A NEW FRAMEWORK FOR PRACTICE, PERFORMANCE, AND PEDAGOGY

DMA PROJECT

A project submitted in partial fulfillment of the requirements for the degree of Doctor of Musical Arts in the College of Fine Arts at the University of Kentucky

By

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Lexington, Kentucky

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2023

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ABSTRACT OF DMA PROJECT

POLYRHYTHMIC PATHWAYS: USING BIMANUAL COORDINATION RESEARCH TO DEVELOP A NEW FRAMEWORK FOR PRACTICE, PERFORMANCE, AND PEDAGOGY

This study reviews and compares percussion literature pertaining to polyrhythms and scientific literature pertaining to bimanual coordination. There exists a gap in the pedagogical approach to polyrhythms, and there is much disagreement between common instructional methods, especially when considered against the findings of several bimanual coordination studies. The purpose of this study is to reveal insight to the percussion community that the learning of polyrhythms is facilitated by the brain in novel ways, and the uniqueness of this learning process requires a rethinking of the current pedagogical approach. Percussion articles, method books, popular literature, and music scores are surveyed alongside primarily neuroscience research on bimanual coordination regarding the nervous system, perception, feedback, and error. The results show that limb independence as a concept must be divorced from polyrhythmic coordination, and tools used in the learning process must promote an internalization of the polyrhythm as a composite coordination pattern. The implications of this study are that a unique curricular approach is necessary for polyrhythmic learning, and, though antithetical to common practice methods, a brute-force approach may be optimal for idiosyncratic coordination patterns in the percussion musical literature.

KEYWORDS: bimanual coordination, percussion, polyrhythm, music, motor skills

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April 14, 2023

Date

POLYRHYTHMIC PATHWAYS: USING BIMANUAL COORDINATION RESEARCH TO DEVELOP A NEW FRAMEWORK FOR PRACTICE, PERFORMANCE, AND PEDAGOGY

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Part One

Polyrhythmic Pathways: Using Bimanual Coordination Research to Develop a New Framework for Practice, Performance, and Pedagogy

Polyrhythms are commonplace in the percussion repertory, and this tradition is historic and global. Currently, the term *polyrhythm* is used primarily to refer to overlapping rhythms in which one unit is equal in length to the other unit regardless of the number of subdivisions (for instance, a three-tuplet and a five-tuplet simultaneously occupying the space of one metronomic beat). Technically, this is *polymeter,* but the terms are often used interchangeably. From an Afro-Cuban bell pattern to the timpani works of Elliot Carter, the simultaneous performance of two rhythmic pulses is inescapable for modern percussion performers, students, and pedagogues. The method for deciphering polyrhythmic ratios typically involves basic mathematics and some graphing paper, and this method is conventionally understood by collegiate percussionists. Practice methods include the isolation of parts or limbs, creative metronome utilization, slow practice, "feeling it out," and ample repetition.

The topic of bimanual coordination (BC) — the utilization of two limbs to accomplish separate and distinct goals — has existed in the neuroscience literature for decades. Studies have examined the brain in real time during the performance of various tasks that resemble or equate to the percussive performance of polyrhythms. There is a wealth of knowledge to be gained from this literature, and its application to percussion performance and pedagogy could completely reshape curricular focus, particularly in the undergraduate domain.

The study of polyrhythms is especially important for percussionists because of the physical constraints[1] surrounding instrumentation. On any given day, a percussionist may physiologically play one single polyrhythm in several distinct ways via the changing of implements (brushes often use a horizontal, cyclic motion), the setup of instruments (multiple percussion setups require movement in-out, up-down, and left-right), the instrument makeup (producing a specific dynamic on a multiple percussion setup requires variable amounts of force that do not easily transfer[2] between instruments), etc. The scientific literature suggests that each of these various physical conditions requires a unique learning process because, fundamentally, different muscle groups are employed, and perception is wildly dissimilar. Polyrhythms played on a piano, for instance, use homologous[3] (similar) muscles that all operate in the same fashion and require equal force output to produce identical results anywhere on the instrument. The sheer

[1] For a definition of *constraints*, see Appendix B.
[2] For a definition of *transfer*, see Appendix B.
[3] For a definition of *homologous*, see Appendix B.

number of contextual variables, combined with the immense cognitive[4] demand required to learn polyrhythms, makes this topic an issue that is unique to percussionists.

Canonical works such as Michael Gordon's (1997) *XY*, Iannis Xenakis's (1991) *Rebonds*, Michio Kitazume's (2021) *Side by Side,* Brian Ferneyhough's (1995) *Bone Alphabet,* Alejandro Viñao's (2001) *Khan Variations,* and Per Nørgård's *I Ching* contain some of the most difficult to perform rhythmic material in the standard repertoire. Despite this, it is a common expectation for undergraduate percussion majors to tackle at least one of these during their studies. The percussion method-book literature neglects the explicit study of polyrhythms, and while scholarly articles, in journals such as *Percussive Notes,* provide tools to understand and practice these complex skills, the information lacks comprehensiveness and is often misguided.

A cursory scan of nervous system literature on coordination[5] and motor consolidation[6] provides just enough evidence to jump hastily and excitedly to certain conclusions. Much of the dissemination of this information in the music community likely stems from the increase in popularity of brain research, as evidenced by non-fiction books such as Daniel Levitin's (2006) *This is Your Brain on Music* and Oliver Sach's (2008) *Musicophilia*. It is increasingly known, for example, that repeated actions cause an increase in myelination[7] (insulation) of the neural pathways for those actions (Luo, 2021). The result is that these neural signals fire more rapidly, and this is sometimes argued to be the mechanism through which automaticity (the ability to perform an action without thinking about it, often referred to as *muscle memory*) arises. It would seem reasonable to conclude that making mistakes in practice could inadvertently reinforce incorrect neural pathways, leading to an increase in performance error. It would then also be reasonable to conclude that practicing slow enough to prevent any errors from occurring is optimal. However, the scientific literature disagrees with this conclusion, and the only way to circumvent these misunderstandings is to perform a thorough review and attempt to understand the mechanisms behind specific processes. It turns out that the learning of polyrhythms is facilitated by the brain in novel ways dependent upon several contextual variables, and the uniqueness of this learning process requires a rethinking of the current pedagogical approach.

The percussion literature surrounding polyrhythms primarily focuses on drumset coordination exercises and suggestions for learning and practice. Articles that consider general coordination provide a window into basic thinking about practice strategies (Ashley, 1984;

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[4] For a definition of *cognitive*, see Appendix B.
[5] For a definition of *coordination*, see Appendix B.
[6] For a definition of *consolidation*, see Appendix B.
[7] For a definition of *myelination*, see Appendix B.

Derrick, 2000; Ruttenberg, 2002; Karre, 2012). Specific polyrhythm guides and suggestions are ample, covering step-by-step methods, overviews, and suggestions for incorporation into practice (Clayton, 1972; Delp, 1972; Kettle, 1981; Macdonald, 2002; Magadini, 1975; Moore, 1996; Prebys, 1971; Venet, 2017). Some articles are tangentially related to perception and its impact on polyrhythmic practice and performance (Abbott, 1994; Leake, 2011; Staebell, 2015; Workman, 2001), while others focus specifically on the application of cognitive science concepts to motor coordination (Artimisi, 2013; Killingsworth, 1995; Piper, 2008; Workman, 2012). Throughout, there exists glaring disagreement with the scientific literature, but the way in which percussionists think about polyrhythms is apparent, and this perspective reflects a layer of abstraction that is discussed at length in the cognitive studies about perception.

The scientific literature surrounding BC (used to perform polyrhythms) focuses on a variety of different areas. Studies that analyze the relationship between brain structure and coordination focus on the corpus callosum (CC) (Bonzano et al., 2008; Eliassen et al., 1999; Eliassen et al., 2000; Fling et al., 2011; Johansen-Berg et al., 2007; Larson et al., 2002; Muetzel et al., 2008; Serrien et al., 2001; Sisti et al., 2012), the ventral medial wall areas (Stephan et al., 1999), the somato-motor cortex and supplemental motor area (Cardoso et al., 2001; Debaere et al., 2001; Jäncke et al., 2000; Kagerer et al., 2003; Johansen-Berg et al., 2007), and the motor, sensorimotor, and parietal cortexes (Boonstra et al., 2007; Caaeyenbergh et al., 2011; Chieffo et al., 2016; Eliassen et al., 1999; Kagerer et al., 2003; Seidler, 2011). Expanding on this conversation later in the literature, studies begin to focus on the communication within and between hemispheres of the brain via neural crosstalk (Diedrichsen et al., 2003; Hoyer & Bastian, 2013; Kagerer et al., 2003; Kennedy et al., 2013, 2015, 2016; Shea et al., 2016) and interhemispheric inhibition (IHI) (Fling & Seidler, 2011; Fling et al. 2011; Kuo & Fisher, 2020; Sisti et al., 2011; Wahl et al., 2016).

Many studies explore the linkage between limbs on a cognitive, perceptual level. These include focuses on the coupling of limbs (Buchanan & Ryu, 2006, 2012; Diedrichsen et al., 2003; Hoyer & Bastian, 2013; Kennedy et al., 2015, 2016; Mechsner & Knoblich, 2004; Weigelt & Cardoso, 2003), perception of action (Bogacz, 2005; Brandes et al., 2017; Debaere et al., 2003; de Poel et al., 2008; Diedrichsen et al., 2003; Hodges et al., 2003; Ivry et al., 2003; Kennedy et al., 2013; Klapp et al., 1998; Kurtz & Lee, 2003 Mechsner & Knoblich, 2004; Michaels et al., 2017; Oliveira & Ivry, 2008; Shea et al., 2016; Yeganeh Doost et al., 2017), and handedness or the role of limbs (Amazeen et al., 1997; Boonstra et al., 2007; Buchanan & Ryu, 2012; de Poel et al., 2008; Dyer et al., 2017a; Gooijers et al., 2013; Hoyer & Bastian, 2013; Peper et al., 1995a, 1995b; Kennedy et al., 2016; Klapp et al., 1998; Sisti et al., 2001).

Throughout the course of these studies, feedback (FB) is discussed at length since it is a fundamental mechanism for experimental control. Some studies focus specifically on the effects of visual FB (Amazeen et al., 2008; Boyles et al., 2012; Gooijers et al., 2013; Hodges et al., 2003; Hu & Newell, 2011; Hurley & Lee, 2006; Wahl et al., 2016; Weigelt & Cardoso, 2003;), while others focus on auditory FB (Dyer et al., 2017b, 2017a; Kuo & Fisher, 2020), both visual and auditory FB (Bogacz, 2005; Peper et al., 1995b; Ronsse et al., 2011; Sisti et al., 2011), or haptic FB (Squeri et al., 2012).

Lastly, much of the BC literature is concerned with error. Areas of focus include the relationship between speed/frequency and mistakes (Bogacz, 2005; Buchanan & Ryu, 2006; Kuo & Fisher, 2020; Lee et al., 1996; Peper et al., 1995a, 1995b; Sisti et al., 2011; Wahl et al., 2016), symmetry between the limbs and their physiology (Brandes et al., 2017; Byblow et al., 1994; Kagerer et al., 2003; Kennedy et al., 2013, 2015; Kuo & Fisher, 2020; Mechsner & Knoblich, 2004; Sisti et al., 2011), and the effects of training on bimanual skill acquisition and performance (Bogacz, 2005; Hodges et al., 2003; Hurley & Lee, 2006; Johansen-Berg et al., 2007; Lee et al., 1996; Peper et al., 1995a).

The purpose of this study is to apply the findings from the scientific literature regarding BC to a new pedagogical framework for the learning of polyrhythms. This will be accomplished with a literature survey, comparison, and pedagogical sequence construction. The literature survey will include scientific journals, non-fiction books, percussion method books, percussion music scores, and percussion journals. The comparison will identify trends in percussion pedagogy that align well with aspects of the literature on BC, and it will criticize deficits in common approaches to learning polyrhythms. The pedagogical sequence will apply concepts from the scientific literature to a new model for incorporating polyrhythms into the practice routine.

Chapter 1: The Nervous System and Bimanual Coordination

BC[8] is the movement of two limbs simultaneously, though the term will primarily be used to mean any coordination between two limbs that requires complex cognitive functioning and approximates the performance of a polyrhythm. The nervous system is the fundamental mechanism by which BC is facilitated. All facets of the learning process can be traced back to functions of this system, and it will serve as the template for understanding the various

[8] BC, *bimanual coordination*. For a list of abbreviations, see Appendix A.

complexities of BC. While the brain will be discussed at length, the nervous system comprises signal pathways throughout the entire body, including peripheral nerves that activate muscles and dense pathways in the spinal cord. Every action taken by the human body, voluntary or involuntary, is the result of cells sending electrical and chemical signals across complex networks. These cells are called neurons,[9] and they have three primary parts: a cell body, dendrites[10], and an axon.[11] Dendrites receive information from the axons of other neurons. This communication occurs at a synapse,[12] whereby electrical signals are converted to chemical signals and then back to electrical signals. Because of this chemical translation and the need for neurons to be highly flexible and adaptable, there is no physical connection between cells. Neurons attach, detach, and reattach synapses forming a highly variable and environmentally influenced network unique to each individual. When a pathway needs to be more efficient, special glial cells coat axons with myelin, forming a myelin sheath[13] akin to insulation on an electrical wire. There are many types of neurons, some of which inhibit signals in the brain instead of exciting pathways. These inhibitory interneurons[14] are particularly important for BC, and this relationship is linked to specific structures in the brain. In illustrating these various structures and the ways in which signaling is overloaded and inhibited, the complexities of BC will begin to emerge, and the need for a new approach to learning polyrhythms will become clear.

Brain Structure

Of the brain areas involved in BC, the CC[15] is arguably the most important. The CC is responsible for communication between the hemispheres of the brain, and since each hand is controlled by a different hemisphere, this signal facilitation is critical for BC. However, neural networks are vast and far-reaching, so describing specific brain regions as having isolated specialties is problematic (Schwarzlose, 2021; Swanson, 2012). Portions of the CC seem to correlate with various facets of BC, but without the cooperation of other brain areas, the CC is useless. This interconnectedness is an inherent aspect of brain function, and it must be recalled periodically. The literature on brain structure and BC reveals that specific brain regions are involved with BC, three primary factors—musical training, speed of movement, and

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[9] For a definition of *neurons*, see Appendix B.
[10] For a definition of *dendrites*, see Appendix B.
[11] For a definition of *axon*, see Appendix B.
[12] For a definition of *synapse*, see Appendix B.
[13] For a definition of *myelin sheath*, see Appendix B.
[14] For a definition of *interneurons*, see Appendix B.
[15] CC, *corpus callosum.* For a list of abbreviations, see Appendix A. For a definition, see Appendix B.

handedness[16]—affect the way these brain regions activate, the CC is the primary mediator for signaling between hemispheres, and the success of the CC in aiding BC is determined significantly by the way in which the goal is represented to the performer. These insights shed light on the unique qualities of BC as evidenced by structural distinction in the brain, and though specific mechanisms exist to facilitate signaling idiosyncrasies during BC, the structure of the brain serves as the foundation for these mechanisms.

The relationship between brain structure and BC has been studied extensively. Everyday motor skills, such riding a bicycle, require the utilization of several brain areas in tandem. These areas specialize, but they collaborate and communicate with one another in order to achieve specific goals. In the frontal lobe, the prefrontal cortex[17] plans voluntary movements, and the motor cortex[18] controls these movements—later smoothed by the basal ganglia—in concert with adjacent secondary areas. The motor areas[19] exist symmetrically in both hemispheres of the brain, and they operate the limbs on the contralateral[20] (opposite) side of the body. In the parietal lobe,[21] the somatosensory cortex processes senses on the skin in conjunction with an association area that receives sensory input and aids in identifying objects and locating limbs in space. Meanwhile, the CC aids in communication between hemispheres of the brain (particularly important when right and left limbs act simultaneously), and the cerebellum[22] helps to control the speed, direction, and force of movement. While these various regions of the brain have typical functions, specific lobes behave in interesting ways when tasked with the execution of a complex bimanual[23] maneuver such as the performance of a polyrhythm. (Garrett & Hough, 2015)

Different brain areas seem to aid in specific aspects of BC, and this process is affected by variables such as musical training, speed of movement, and handedness. Despite the generalized functions of each brain region, the coordination of limbs on merely one side of the body requires the cooperation of several areas distributed throughout the motor network on the surface of the brain and deep beneath the cortex (Debaere et al., 2001). For example, while most motor areas control limbs on the opposite side of the body, the secondary somatosensory areas activate

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[16] For a definition of *handedness*, see Appendix B.
[17] For a definition of *prefrontal cortex*, see Appendix B.
[18] For a definition of *motor cortex*, see Appendix B.
[19] For a definition of *motor area*, see Appendix B.
[20] For a definition of *contralateral*, see Appendix B.
[21] For a definition of *parietal lobe*, see Appendix B.
[22] For a definition of *cerebellum*, see Appendix B.
[23] For a definition of *bimanual*, see Appendix B.

bilaterally[24] (on both sides) regardless of which limbs are in use (Kagerer et al., 2003). The sensory areas[25] and prefrontal cortex are pivotal for task-switching,[26] a skill required in nearly all performance scenarios (Caeyenberghs et al., 2011). The parietal cortex[27] coordinates direction and spatial aspects of oppositional movements, and the primary sensorimotor cortex[28] and somato-motor cortex[29] are more active for the hand that moves fastest (Caeyenberghs et al., 2011; Eliassen et al., 1999; Jäncke et al., 2000). In trained pianists, the primary cortex and the intrasulcal length of the precentral gyrus[30] are more symmetrically organized, implying that the pianist brain tends not to favor limbs, while the brain of a nonmusician favors the dominant limb (Chieffo et al., 2016). The act of practicing may be the culprit, as neural activity is reorganized for the slow hand during the acquisition of a novel bimanual skill (Boonstra et al., 2007). It would be incorrect, however, to assume that this restructuring of the brain due to practice makes it easier to learn new bimanual skills. BC is unique because of an area between, not within, these brain regions.

The function of the CC may be best described by outlining the difference between gray and white matter[31] in the brain. Myelin sheaths, formed around axons by glial cells in order to increase the transmission speed of neural pathways, appear white in color. The cell bodies and dendrites of the neurons appear gray (Garrett & Hough, 2015). The CC is a densely packed region of white matter that connects the two hemispheres of the brain, and axons reaching through from one side to another enable communication between the two sides (Garrett & Hough, 2015). This brain region is significantly difficult to study because of its involvement in such a wide variety of operations. Recently, diffusion tensor imaging[32] (DTI) has allowed researchers to examine the strength and directionality of tissue in the CC, measured with fractional anisotropy (FA). This metric helps to determine the "permeability of myelin sheaths, changes in the orientation of axons, differences in axon-packing density, and the thickness of myelin and axonal caliber," providing an effective variable for experimental comparison between subjects (Sisti et al., 2012, p. 353). Since the structural integrity of white matter is correlated with BC ability

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[24] For a definition of *bilateral*, see Appendix B.
[25] For a definition of *sensory area*, see Appendix B.
[26] For a definition of *task-switching*, see Appendix B.
[27] For a definition of *parietal cortex*, see Appendix B.
[28] For a definition of *sensorimotor cortex*, see Appendix B.
[29] For a definition of *somato-motor cortex*, see Appendix B.
[30] For a definition of *intrasulcal length of the precentral gyrus*, see Appendix B.
[31] For a definition of *white matter*, see Appendix B.
[32] For a definition of *diffusion tensor imaging*, see Appendix B.

(Bonzano et al., 2008; Fling et al., 2011; Fling & Seidler, 2011; Gooijers et al., 2013; Johansen-Berg et al., 2007), and FA indicates structural integrity via increased myelination (Muetzel et al., 2008), DTI continues to be immensely useful for studying such a complex neural process. Prior to this method, subjects with dysfunctional corpus callosa—due to multiple sclerosis,[33] traumatic brain injury[34] (TBI), or callosotomy[35]—were studied while attempting to perform various bimanual tasks.

A study using acallosal[36] patients found the CC to be pivotal for BC as early as 1988 (Jeeves et al.). Since then, distinctions have been made between functions of the anterior[37] and posterior[38] regions of the CC, but these distinctions are impacted heavily by other brain regions that communicate through these specific portions of the CC. For example, variations in bimanual performance ability have accompanied differences in the CC paths connecting the supplemental motor area[39] and the ventral medial wall area[40] (Johansen-Berg et al., 2007). The functions of brain regions connected by the CC are virtually inseparable from the functions of the CC itself, which mediates the multiplicity of goals from each hemisphere. Nevertheless, the anterior CC seems responsible for coordinating movement timing in relation to internal cues such as proprioception[41]; the posterior, external cues such as visual information (Eliassen et al., 2000). The posterior CC may also be critical for direction coordination and the integration of visual and visuospatial[42] information (Eliassen et al., 1999; Bonzano et al., 2008). While these distinctions are useful, they fail to illuminate one of the most critical modulators of brain function in regard to BC.

Goal-orientation has an immense impact on the successful execution of BC tasks. While natural goal-directed BC tasks, such as opening a drawer, do not rely heavily on communication between hemispheres, interactions across the CC are necessary for the synchronization of limbs in novel actions that require persistent attention and supervision (Serrien et al., 2001). It is clear that some bimanual skills are more challenging than others, and this is represented in the activity of the CC which is more stimulated during tasks that require the limbs to operate with

[33] For a definition of *multiple sclerosis*, see Appendix B.
[34] For a definition of *traumatic brain injury*, see Appendix B.
[35] For a definition of *callosotomy*, see Appendix B.
[36] For a definition of *acallosal*, see Appendix B.
[37] For a definition of *anterior*, see Appendix B.
[38] For a definition of *posterior*, see Appendix B.
[39] For a definition of *supplemental motor area*, see Appendix B
[40] For a definition of *ventral medial wall area*, see Appendix B.
[41] For a definition of *proprioception*, see Appendix B.
[42] For a definition of *visuospatial*, see Appendix B.

separate goals. Bonzano et al. (2008) suggests that coordination errors in multiple sclerosis patients could result from deficits in motor programming[43] instead of sensorimotor transmission in the CC. The way in which a task is presented has a deep impact on the brain's strategy for completing that task.[44] When it comes to complex BC, the brain can send signals that inhibit transmission instead of activating it. Signals in the CC are either constructive and excitatory,[45] promoting the activation of neural signals, or destructive and inhibitory, impeding the activation of neural signals (Bonzano et al., 2008). Inhibitory signals are well understood, and they function as a result of excitatory signals that travel across hemispheres and activate interneurons which then inhibit signals in that contralateral hemisphere (Fling et al., 2011). According to Bonzano (2008), constructive signals are sent when the performer's limbs are working on a common goal, and destructive signals are sent when the performer's limbs are working on a separate goal. While this is an oversimplification, it does illustrate the pivotal role goal-orientation plays in determining the brain's strategy for coordinating complex bimanual movements. In addition to mediating signals that activate muscles, the CC clearly aids in keeping the limbs from mirroring[46] one another during bimanual performance, and the way in which the goal is perceived helps to determine the CCs effectiveness in this endeavor.

Brain Structure in the Percussion Practice Room

In a study investigating temporal[47] control in patients with congenital as well as acquired damage to the CC, Serrien et al. (2001) had subjects perform a drawer-opening task and a rhythmic circling movement executed in an inphase (same rate) and antiphase (different rates) mode. The findings showed that learning novel bimanual tasks that require constant attention necessitates communication between hemispheres via intact callosal[48] fibers. It has also been shown that simultaneous and sequential limb movements are treated differently by the brain (Stephan et al., 1999). These discoveries imply that the brain approaches polyrhythms in a distinct manner, and they attest to the necessity of a uniquely curated learning process.

This challenge is exacerbated by multiple-percussion setups which vary in instrument layout and orchestration. The novelty of each setup requires the performer to learn new motor patterns specific to that set of instruments, significantly increasing cognitive load during the

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[43] For a definition of *motor programming*, see Appendix B.

[44] For more information on the effects of attention on motor performance, see *constrained action hypothesis* in Appendix B.

[45] For a definition of *excitatory*, see Appendix B.

[46] For a definition of *mirroring*, see Appendix B.

[47] For a definition of *temporal*, see Appendix B.

[48] For a definition of *callosal* see Appendix B.

learning and performance of polyrhythms. Young adults with TBI[49] and controls performed object manipulation and cognitive control tasks while seven specific subregions[50] of the CC were examined using DTI[51] (Caeyenberghs et al., 2011). The study showed that disruptions in communication between hemispheres severely impact the performance of directionally disjunct movements. Additionally, Kagerer et al. (2003) found success rates to be more variable during asymmetric bimanual inphase and antiphase circling tasks. These studies illustrate the importance of the CC in navigating a multiple-percussion setup, and they highlight the relationship between movement symmetry and polyrhythmic timing. While it may seem that separating horizontal movement from vertical movement during practice—beginning the learning process on a snare drum practice pad for instance—would prove beneficial, the integrated nature of these motions requires an integrated approach to acquisition. Learning the polyrhythm away from the multiple-percussion setup may indeed aid in the *understanding* of that polyrhythm, but the skill will not transfer when the horizontal component is introduced to the limbs. The brain does not separate the rhythm from the movement; the movement *is* the rhythm.

To further complicate matters, limbs are not treated equally by the brain, and specific quirks arise when BC is attempted. Jäncke et al. (2000) identified two variables related to the limbs, hand dominance and frequency, that affect brain signaling during BC. Furthermore, in a study of nine healthy adults who learned a bimanual 3:5 (three beats with one finger and five beats with the other) polyrhythmic tapping task, cortical[52] modulations of event-related beta activity were monitored.[53] Event-related beta modulation was enhanced in the contralateral motor cortex of the slow finger, indicating a reorganization of neural activity in the slow hand (Boonstra et al., 2007). Because of this reorganization, it was determined that the slow hand must be interleaved into the timing of the fast hand for successful bimanual skill acquisition. This determination neglects to address handedness, but Chieffo et al. (2016) showed an increase in brain symmetry of the motor areas of pianists, which implies that the effects of handedness may diminish with practice regardless.

It is not the case, however, that isolating the fast and slow limbs prior to interleaving the slow hand into the polyrhythm is helpful. Since Debaere et al. (2001) found that several brain

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[49] TBI, *traumatic brain injury*. For a list of abbreviations, see Appendix A.
[50] For a definition of *subregions*, see Appendix B.
[51] DTI, *diffusion tensor imaging.* For a list of abbreviations, see Appendix A.
[52] For a definition of *cortical*, see Appendix B.
[53] For a definition of *monitor*, see Appendix B.

areas are involved even when ipsilateral[54] (same side) limbs are used, the concept of limb independence is not mirrored in the structure of the brain even when transcallosal[55] communication is less vital. The limbs are not treated as discrete units, even though the brain seems to prioritize the dominant hand and the faster hand as focal points during the performance of polyrhythms. A similar phenomenon occurs with sensory information, as proprioception (awareness of the position or movement of the body) and visual information are addressed by different areas of the brain (Eliassen et al., 2000). Both of these stimuli are integral to the learning process despite the performer's inability to focus on them in tandem.

Though not inherently present in all performance situations equally, task-switching is necessary and compounds the difficulty of polyrhythmic performance by increasing the signaling of the hand with the higher force (Hoyer & Bastian, 2013). Switching between tasks requires a completely different usage of brain regions—recall that the prefrontal cortex is heavily involved with decision making but does not seem to play a major role in BC—and requires a separate skillset. While the CC does indeed help to facilitate this skill (Caeyenberghs et al., 2011), the activity in this brain area adjusts inhibition[56] and excitation depending on the task at hand (Muetzel et al., 2008). The more task-switching is required; the more difficult BC becomes. It stands to reason that practicing the transitions between tasks that are adjacent to the polyrhythm itself should be considered an essential element of practice. For example, a 3:2 polyrhythm performed between a conga and tom-tom in a multiple-percussion setup will suffer from errors the moment that same polyrhythm transitions to the bongo and bass drum. Even though this horizontal movement between drums is not typically difficult, it is integral to the performance of the polyrhythm and therefore must be intentionally addressed.

Many issues with polyrhythmic learning become simpler to undertake when the process of *understanding* the coordination is divorced from the act of performing itself. According to Bonzano et al. (2008), errors in BC occur prior to action. Therefore, understanding the exact proportional relationship between the notes in a polyrhythm is not enough to ensure successful execution. The brain will still encounter obstacles while attempting to communicate that understanding to the limbs just before movement occurs. These neural acrobatics can produce a bizarre sensation in which a performer's limbs seem incapable of producing an action clearly dictated by thought. MS patients and control subjects performed unimanual[57] and BC tasks in a

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[54] For a definition of *ipsilateral*, see Appendix B.
[55] For a definition of *transcallosal*, see Appendix B.
[56] For a definition of *inhibition*, see Appendix B.
[57] For a definition of *unimanual*, see Appendix B.

study that explored the relationship between callosal dysfunction and BC deficits (Larson et al., 2002). The CC deficits of the MS patients affected response time instead of accuracy, implying that the CC negotiates the timing of notes differently than the coordination of limbs. This negotiation produces a situation in which a typical performer may accurately execute the timing elements of a polyrhythm, because of a clear understanding of the rhythmic proportions, while simultaneously using an inappropriate hand sequence to do so. These studies reinforce the idea that learning a polyrhythm doesn't begin until the exact sequence of motor actions is attempted by the performer.

Another critical factor in BC ability is age. In a study that investigated whether age differences in callosal structure and interhemispheric[58] function contribute to variability in the performance of complex BC tasks in older adults, Fling & Seidler (2011) had subjects perform unimanual, bimanual simultaneous, and bimanual independent force production tasks while examined with DTI. The study ascertained that the way in which limbs are inhibited changes in older adults, causing deficits in BC. Structural integrity and plasticity diminish as well (Fling et al., 2011), and while this leads to general declines in ease of learning, inhibition is particularly crucial for the learning of polyrhythms. Since skill transfer is relatively absent for polyrhythms (Hurley & Lee, 2006), it seems that the learning of complex coordination patterns should be learned early in the percussion performance career. This may seem counterintuitive since the complexity of polyrhythms understandably aligns them with advanced curricular studies. However, the lack of skill transfer for these abilities indicates that the challenge is significant regardless of the moment in which it is confronted.

The process of learning a polyrhythm can be thought of as overcoming malfunctions in signaling within the nervous system. When one motor area sends a signal to the contralateral hemisphere to operate the hand on the opposite side of the body, it sends that same signal to the ipsilateral pathways in its home hemisphere (Kagerer et al., 2003). Limbs have a tendency to mirror one another because of this two-sided signaling (not ideal when they have separate goals), and the brain must learn how to inhibit one of the limbs properly for specific bimanual tasks. It would be easy to conclude that the slow hand needs to be inhibited, but the complexities of IHI[59] are not that transparent. While the process of learning a polyrhythm might get easier over time—as evidenced by the fact that some people have slight predispositions to the learning of new bimanual skills when exposed at key ages (Johansen-Berg et al., 2007)—the

[58] For a definition of *interhemispheric*, see Appendix B.
[59] IHI, *interhemispheric inhibition*. For a list of abbreviations, see Appendix A.

execution of a novel polyrhythm itself does not significantly benefit from past experience. Despite this hurdle, a better understanding of IHI and neural crosstalk will shed light on the mechanics of the problem so that it may be addressed head-on.

Neural Crosstalk and Interhemispheric Inhibition

When one limb operates, the brain inhibits the tacet limb so that it does not copy the target limb. This typically works very well, but the cognitive load increases when both limbs are in operation.[60] In this scenario, both limbs are activated and inhibited simultaneously, and there are a multitude of crossed pathways between hemispheres. With complex BC, such as polyrhythmic tasks, the similarity of movement and slightly offset rate of signaling creates a convoluted atmosphere in the brain that leads to mistakes in processing and failures in performance. Elucidating the peculiar nature of polyrhythms, the literature on neural crosstalk and IHI reveals that signals for each limb are also sent to the other limb causing coupling[61] (mirrored movements) between the limbs. Coupling must be inhibited for successful BC, and skill complexity largely determines the need for inhibition. These revelations have counterintuitive implications for the learning of polyrhythms, and shedding light on neural crosstalk and IHI will help to define the major obstacles in skill acquisition.

Neural crosstalk[62] occurs when a portion of the signals sent contralaterally to the target limb are also sent ipsilaterally to the nontarget limb (Kagerer et al., 2003). This signaling spreads to the nontarget hand two ways—through mirror-activated contralateral cortical sites and ipsilateral corticospinal[63] pathways—and can be conceptualized as crossed and uncrossed output connections (Kennedy et al., 2013). When the same information is conveyed to both hemispheres of the brain in this manner, the result is unintended mirrored movements in the limbs (Kennedy et al., 2015). It follows unsurprisingly that neural crosstalk can diminish bimanual performance since the goal is often for limbs to display an apparent independence (Shea et al., 2016). However, because of the complexities inherent in crosstalk, it is not always the case that BC suffers (Kennedy et al., 2015). These complexities include variations in the way neural crosstalk effects execution, motor planning, reaction time, and muscle homology. For example, while negative effects of neural crosstalk can be seen in a learned asymmetric bimanual

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[60] For more information on the effects of increased cognitive load, see *motor overflow* in Appendix B.

[61] For a definition of *coupling*, see Appendix B.

[62] For a definition of *neural crosstalk*, see Appendix B.

[63] For a definition of *corticospinal*, see Appendix B.

isometric[64] (force applied without muscle contraction) pinching task, the processes that control execution and motor planning are affected differently depending on the task demands (Hoyer & Bastian, 2013). Additionally, neural crosstalk can influence reaction times to stimuli when contralateral muscles are activated (Kennedy et al., 2013), and it presents differently depending upon whether nonhomologous or homologous muscles are used (Kennedy et al., 2015). As with structural correlations to BC, neural crosstalk is highly sensitive to the various complexities of movement. While the coupling of movement due to replicative signaling can prove problematic, the brain deploys a compensatory mechanism that inhibits some of this signaling. This process allows for the decoupling of movement, but it comes with its own intricacies.

Isochronous movement (coupling of the limbs) must be inhibited in order to perform multifrequency movements such as polyrhythms (Sisti et al., 2011). IHI[65] is accomplished when excitatory axons, via transcallosal glutamatergic[66] pathways, synapse onto pyramidal tract neurons[67] through gamma-aminobutyric acid (GABA) inhibitory interneurons in the contralateral cortex (Fling et al., 2011; Fling & Seidler, 2011). The signal sent to the target limb is also sent as an excitatory signal to the nontarget limb, and the nontarget signaling gets translated into an inhibitory signal which keeps the nontarget limb from performing the exact motions of the target limb. The great epiphany revealed by IHI is that the difficulty of learning a complex bimanual skill arises because limbs must be inhibited. It is almost as if BC is a process of *unlearning* instead of learning. The very nature of IHI necessitates a unique skill acquisition process, and it requires the learning of bimanual skills with both limbs simultaneously (Kuo & Fisher, 2020).

The correlations found in the IHI literature are often contradictory. While earlier studies do highlight the pivotal role of age and training in the function of IHI during the learning process, recent studies have made it clear that task complexity is a primary factor. In one study, higher IHI was correlated with poorer BC, but it was also found that IHI is modulated to meet specific task demands in young adults and that the role of IHI shifts as a function of age. Older adults use less IHI and seem to benefit from neural crosstalk, though this shift results in a general decline of BC (Fling et al., 2011). More recently, greater IHI corresponded to asymmetric BC, and stronger IHI and structural integrity—measured with transcranial magnetic stimulation[68] (TMS) and FA[69]—in

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[64] For a definition of *isometric*, see Appendix B.
[65] For a definition of *interhemispheric inhibition*, see Appendix B.
[66] For a definition of *glutamatergic*, see Appendix B.
[67] For a definition of *pyramidal tract neurons*, see Appendix B.
[68] For a definition of *transcranial magnetic stimulation*, see Appendix B.
[69] FA, *fractional anisotropy*. For a list of abbreviations, see Appendix A.

the area connecting primary motor cortex hand regions predicted better BC (Wahl et al., 2016). While musicians have been shown to have both lesser and greater IHI than controls (Fling et al., 2011; Fling & Seidler, 2011), Kuo & Fisher (2020) found that bimanual tasks with a higher demand correlated with higher IHI in musicians. These findings imply that IHI becomes more necessary as the similarity between actions in each hand decreases, and young adult brains do not tackle BC in the same manner as older adults. Further, they illustrate that BC alone does not require significant cognitive demand. The complexity of the task is paramount, and polyrhythms in the percussion idiom exemplify this complexity.

Neural Crosstalk and IHI in the Percussion Practice Room

Interference in BC occurs as a result of neural crosstalk, and IHI must be reinforced through practice for specific tasks in order to mitigate the effects of this crosstalk.[70] Some movement criteria have a greater effect on interference than others. In a study designed to determine whether the activation of a muscle group used to produce the ongoing movement of one limb influenced the initiation or reaction time of elbow movements in the contralateral limb, Kennedy et al. (2013) had right-handed participants produce a pattern of flexion and extension movements defined by a sine wave with the right limb. Subjects were instructed to react as quickly as possible via flexion and extension of the left limb when the color of the sine wave shifted. The study showed that direction of movement has an impact on signal interference. While the movement in this study was continuous as opposed to discrete and rhythmic, it does mimic the horizontal component of percussion playing on keyboard instruments and multiple percussion. Therefore, learning on an instrument (or instruments) in which the playing surface is variable can lead to an increase in reaction times.

Further probing the effects of crosstalk on BC, Kennedy et al. (2015) set out to determine whether the activation of homologous and nonhomologous muscles resulted in different patterns of distortions in one limb related to the forces produced by the other. Subjects rhythmically produced a 1:2 pattern of isometric forces with the arms, and FB[71] was provided to reduce perceptual and attentional constraints. The study found that neural crosstalk manifests differently depending upon whether similar or different muscles are used, and slight errors in one limb can cause the coordination to collapse into a more stable pattern. Similarly, Wahl et al. (2016) found that IHI is greater in asymmetric movements in a study meant to better understand

[70] For more information on the role of interference in performance preparation, see *contextual interference* in Appendix B.

[71] FB, *feedback*. For a list of abbreviations, see Appendix A.

how the brain overrides default inphase movements to enable multifrequency patterns between the hands using subjects that performed a visually cued bimanual tapping task. An increase in IHI for asymmetric movements (in which the limbs travel in different directions) implies that tasks requiring similar motions in the limbs may be more prone to unintentional mirroring. In a percussion performance scenario, using similar stroke types with each hand on a single instrument, such as performing polyrhythms on a snare drum, may produce a greater challenge for the hands in terms of decoupling the movements since the inhibitory mechanisms in the brain are less active.

Despite the interplay between movement execution and interference, signaling issues arise at very specific times unequally throughout the learning process. Diedrichsen et al. (2003) attempted to identify the locus[72] of interference observed during the preparation of bimanual reaching movements in a study that included four experiments using right and left-handed target locations specified by color (same or different), amplitude[73], and direction, with distractors presented corresponding to responses of the opposite hand. The study found that errors tend to occur while selecting a target location, and the effect limbs have on one another is more prominent in early learning stages. More specifically, in a study exploring the effects of various task demands on reaction time and error in the learning of a novel bimanual isometric pinch force task in one experiment with unified goals and another experiment with task interruptions, Hoyer & Bastian (2013) found that error occurs during the motor planning and execution stages. Despite interference taking place prior to playing a note, Kennedy et al. (2013) argue that this interference is not a product of action-planning or perception.[74] The implication is that, while signal interference due potentially to neural crosstalk occurs prior to the movement of limbs, the conscious decisions made by the performer during this period of time are not the culprit. Once again, the performer clearly dictates action that the brain fails to execute.

Beyond contending with neural crosstalk and failures in IHI, the performer is also faced with the repercussions of the limbs as they relate to one another. Kennedy et al. (2016) conducted three experiments in which both limbs were producing a constant force, one limb was producing a dynamic force while the other limb was producing a constant force, and both limbs were producing dynamic force patterns. While trying to determine the level of cooperation or interference observed from the forces generated in one limb on the forces exhibited by the

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[72] For a definition of *locus*, see Appendix B.
[73] For a definition of *amplitude*, see Appendix B.
[74] For a definition of *perception*, see Appendix B.

other, the researchers discovered that one limb tends to impact the other when it is dominant, faster moving, or making changes. These changes include modifications in trajectory (Diedrichsen et al., 2003) and the production of greater force (Hoyer & Bastian, 2013). In musical terms, one hand will impact the other when it is playing faster, changing rhythms, switching between playing areas, or playing at a louder dynamic level. In each of these cases, the static, slower, softer hand will tend to mirror the other. This effect is compounded with hand dominance, as there is a general tendency for the weak hand to mirror the strong hand. Handedness and role will be examined further, but the relationship between these interlimb[75] effects, neural crosstalk, and IHI is integral to BC.

Thankfully, interference can be reduced. First and foremost, providing ample preparation time to aid in understanding the task can make it easier to decouple the limbs (Hoyer & Bastian, 2013). Percussionists have not been studied as extensively as pianists and wind players, but learning aids are equally compatible when it comes to perception. Kuo & Fisher (2020) investigated the relationship between IHI and BC in keyboard players compared to string players using subjects that performed a force tracking task in symmetric and asymmetric conditions. TMS[76] was used to measure ipsilateral silent period[77] (iSP) to index IHI in both hemispheres of the brain, and it was concluded that learning with the limbs together instead of separated is imperative for complex BC. In order to reduce mirroring, the modern percussionist should spend time understanding the polyrhythm before attempting to play; such that the very first attempt utilizes all necessary limbs in tandem. Knowledge that the dominant, faster, more forceful limb will tend to be mirrored can aid in error detection during the early stages of the learning process. With a better understanding of the nervous system, the problems unique to BC can be circumvented using perception as a primary tool. As with the nervous system, perception interfaces with BC in various ways, and uncovering these peculiarities is the next step to forming a new pedagogical approach for polyrhythms.

Neural crosstalk and IHI, facilitated by structural specializations in the brain, illuminate the substantial obstacles in skill acquisition. Horizontal motion changes the brain's interpretation of a polyrhythm. The slow hand must be interleaved into the timing of the fast hand, and it is important to isolate transitions. Polyrhythmic understanding does not ensure success in motor coordination. The learning of polyrhythms should not be delayed in the modern percussion

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[75] For a definition of *interlimb*, see Appendix B.
[76] TMS, *transcranial magnetic stimulation*. For a list of abbreviations, see Appendix A.
[77] For a definition of *ipsilateral silent period*, see Appendix B.

curriculum. Decoupling might be more difficult when the limbs move similarly. Despite this difficulty, learning with the limbs together instead of separated is a must. The need for a new pedagogical approach concerning polyrhythms is elucidated by the nervous system and its critical role in BC. With a better understanding of the nervous system, the problems unique to BC can be circumvented using perception as a primary tool. As with the nervous system, perception interfaces with BC in various ways, and uncovering these peculiarities is the next step to forming a new pedagogical approach for polyrhythms.

Chapter 2: Perception and Bimanual Coordination

One of the more curious facets of bimanual learning is highly abstract and difficult to formulate into actionable procedures. Two individuals can follow the exact same learning sequence and still have completely different results because the way they think about the task varies. Any method for learning complex BC skills would need to account for differences in perception, ideally forcing a particular mode of perception on the learner. This may seem like quite the impossible task, and it is of course unlikely that any method book could control the mind of its reader. However, tools exist to reframe one's perception, and these have shown various levels of success depending on several controllable factors. Perception is not a hinderance though; it is a potent resource. Wielded with informed intention, perception can dilute the most difficult polyrhythms into singular, easily comprehensible units. Some fundamental complexity exists as a result of the intangibility of this tool, but digging deeper into its mechanisms can help to alleviate any confusion. A thorough understanding of perception and its place in BC will require an examination of the force of attraction between the limbs, their biological and functional predispositions, and the effects of using internal stimuli to inform a general conception of bimanual procedures. To be exact, coupling, handedness and role, internal perception, and external perception require analysis in order to apply perceptual tools to practice and performance. Perception is the critical link between intention and action in the performance of complex bimanual skills, and appreciating this link is a necessary step on the way to cultivating a comprehensive approach to the learning of polyrhythms. The bizarre behavior of limbs during BC provides a window into this insight.

Coupling

When learning a novel bimanual skill, it is common to experience symmetrical movement in the limbs even when unintended. The limbs seem to have a "mind of their own," with a strong preference for mirrored actions. For percussionists, this is often experienced in regard to timing, but the effects of limb coupling reach far beyond the temporal domain. The likelihood of coupling is influenced by specific variables, and navigating these variables is one of the responsibilities of perception. To better understand how perception interacts with the role of each limb, it is important first to clarify the ways in which the limbs interact with one another.

Variables related to trajectory, amplitude, force, and error can increase the likelihood of coupling between the limbs. For instance, when the trajectory of one hand is modified as the result of an obstacle, the trajectory for the other hand is also altered. This type of spatial assimilation is seen when hands draw different shapes or produce fast reversals (Diedrichsen et al., 2003). Similarly, bimanual movements with unequal amplitudes lead to a lengthening of the shorter amplitude. This is likely the result of neural crosstalk, as it is not at all affected by visual stimulus (Weigelt & Cardoso, 2003). Combining concepts, some studies explored differences in circle tracing between the limbs. The larger the difference in diameter; the larger the shift in tracing (Buchanan & Ryu, 2006). There is also a tendency to undershoot the amplitude in both circles when the scaled[78] circle is larger and overshoot when the scaled circle is smaller (Buchanan & Ryu, 2012). These studies show that greater differences in the limbs cause coupling effects to increase, and the coupling has a heavy preference for the limb with a larger trajectory or amplitude.

Force production is also influenced by coupling, as forces produced by one limb are significantly correlated to forces produced by the other. This influence increases when each limb is performing a dynamic task. Surprisingly, even in a simple task— force production with one limb while the other is stationary—the effects of coupling are readily apparent (Kennedy et al., 2016). Any type of perturbation[79] in one limb that pushes it toward the pattern of movement of the other limb could result in a phase[80] transition (the change in frequency of a limb) to 1:1, or unison (Kennedy et al., 2015). As with trajectory and amplitude, changes in force production lead to a coupling of the nontarget limb. Even more problematic, small errors in performance can cause an unintended collapse into a simple bimanual pattern.

Forming the right conceptualization of the bimanual task can help to reduce error. BC may be viewed as hierarchical in nature with interlimb and intralimb[81] synergies assembled independently (Buchanan & Ryu, 2012). While error does occur prior to movement, explicit parameterization of movement is not necessary to coordinate movement (Mechsner & Knoblich, 2004). Amending this conclusion, Hoyer & Bastian (2013) posit that decoupling is manageable

[78] For a definition of *scaled*, see Appendix B.
[79] For a definition of *perturbation*, see Appendix B.
[80] For a definition of *phase*, see Appendix B.
[81] For a definition of *intralimb*, see Appendix B.

when given sufficient time to reach a steady state in the parameterization process, simplifying the command for each limb as a perceptually unified instruction. Once more, a combined approach to BC is suggested, though it does not seem enough to merely learn the task with both limbs. Perception of the task as a singular unit is principal to circumventing the effects of coupling between the limbs.

Coupling in the Percussion Practice Room

The practical takeaway for percussionists is that coupling does not occur without bias, and it can be predicted. It can be difficult to identify and correct errors during practice due to the sheer amount of sensory input and attentional demands. However, these studies reveal that likely coupling errors can be easily identified during task preparation. If a limb is playing softer, slower, reaching a smaller distance, or making fewer adjustments, it is more prone to error because it is likely to mirror the opposing limb. Therefore, the performer can reliably predict where to identify errors for speedy correction.

In a study meant to determine the functional origin of coupling by investigating coordination stability when two fingers of each hand periodically tap together, Mechsner & Knoblich (2004) conducted four experiments with different variables for subjects performing bimanual finger tapping tasks: different finger combinations, full vision and no vision, symmetrical and parallel labels on the fingers, and varied relative hand positions. The study showed that the tendency for limbs to copy each other is independent of the limb or sequence of use, the actual muscle movements are not addressed by the brain in the planning and execution phase of a task, detailed instructions for each limb are not a necessity for movement control, and the likeness of muscles (hand and hand vs hand and foot) does not play a significant role in defining coordination patterns. Since limb sequence does not impact coupling, it would not benefit the learning process to adjust sticking (the order in which each stick or mallet strikes a playing surface).

In a situation where a polyrhythm needs to be performed between the hand and foot, such as on a drumset or a multiple percussion setup with a kick drum, learning the pattern with the hands first may seem like a logical beginning step. However, since coupling is present regardless of muscle similarity, this step would not reduce the tendency for the hand and foot to mirror each other once introduced. As far as coupling is concerned, the task should be learned in its complete form at the outset of acquisition. More pertinent is the absence of muscle movement in the brain’s prescription for the task. Herein lies the importance of perception in reducing coupling between the limbs. Though scripting each movement may aid in *understanding* the polyrhythm, it will not help to execute the pattern because the brain is not actively using that information prior to movement anyway. Instead, the performer should focus on strengthening perception of the composite rhythm and limb coordination as a singular unit. Until this point, the relationship between limbs has been framed as a byproduct of task requirements. Examined more closely, functional roles appear that affect more than the probability of coupling between the limbs.

Handedness and Role

The tendency for one hand to be favored (the dominant hand) is referred to as handedness in the BC literature. There is some debate surrounding the origin of dominance as either a biological difference or an asymmetry in attention. Either way, attention is important in determining the functional role of a limb, and this role is independent of handedness. The role of a limb is determined by aspects of its function in a task (such as its speed) and the performer's perception of that function. If a performer decides to interleave the playing of the right hand into the faster left hand, for example, the left hand would take on a dominant role because of perceptual bias. Handedness is correlated with movement frequency and amplitude, and role is correlated with frequency and force. While the effects of handedness can be mitigated to an extent, the effects of role are more stubborn. Through the interplay between handedness and role, the contribution of perception to BC will be elucidated.

Handedness is one of the major initial factors in bimanual coupling, though it is more apparent in simpler BC tasks. Generally speaking, the nondominant limb tends to be strongly affected (led) by the dominant limb (Amazeen et al., 1997; de Poel et al., 2008; Kennedy et al., 2016), and the dominant limb tends to be more accurate (Gooijers et al., 2013). The effects of dominance are correlated with movement frequency. When the nondominant hand is required to move faster than the dominant hand, error increases (Sisti et al., 2011), and the phase lead (tendency for one hand to lead the other) of the dominant limb is greater in higher frequencies (de Poel et al., 2008). While timing errors increase when the nondominant hand moves faster, amplitude does not suffer in the same manner (Buchanan & Ryu, 2012). Fortunately, the effects of handedness can be mitigated. Sisti et al. (2011) found that hand dominance can be overcome with the use of augmented[82] FB which provides real time information to aid in error correction. It is not clear if the effects due to handedness are biological or attentional, but there is evidence to suggest that perception is yet again the key. According to Amazeen et al. (1997), an inherent attentional bias could be responsible for the effect of handedness on coupling. Further, de Poel

[82] For a definition of *augmented feedback*, see Appendix B.

et al. (2008) suggest that the perceived effects of handedness may actually be an inherent attentional asymmetry as evidenced by the reduction of coupling when attention is focused on the non-dominant limb. It is possible that the performer's perception of one limb as the leader is what drives coupling, due to hand dominance, to take root.

The role of each hand is variable, though handedness initially defines this role in most tasks. The dominant hand is the anchor during motor skill acquisition, but the nondominant hand can steal this role, particularly as a result of frequency and force. When it comes to frequency, the slow hand is influenced by the fast, and the effect does not occur in the opposite direction (Peper et al., 1995a). Not only is the slow hand influenced; it is led by the faster hand (de Poel et al., 2008). The fast hand also tends to perform better than the slow hand, indicating a hierarchical control scheme dependent upon the timing of the faster hand (Peper et al., 1995b). Interestingly, counting along with the slow hand is disruptive (Klapp et al., 1998), a clear indicator that unique roles are assumed by the limbs due to frequency. Differences in force production can also cause roles to shift; the hand producing a greater force causes interference on the hand producing a lesser force (Hoyer & Bastian, 2013). Note that these distinctions are independent of hand dominance, as the role is determined exclusively by the speed or force of one limb relative to another. Reinforcing this point, Peper et al. (1995a) indicate that differences due to handedness are eclipsed by functional roles. These roles are fundamentally inseparable from the tasks themselves. As a result, there is no transfer of skills whatsoever when the hands are swapped (Dyer et al., 2017a). Swapping the hands forces a change in role, disrupting the brain's methodology for tackling the BC pattern. Differences in force and frequency affect the performer's perception of the primary limb, thus perception is intricately linked to the function of role in the learning of bimanual skills.

Handedness and Role in the Percussion Practice Room

The effects of hand dominance may be overshadowed by the role of the limbs, but since attention seems to be the culprit, handedness must be addressed. It may come as no surprise that the dominant hand tends to be more accurate (Gooijers et al., 2013) and has a greater influence on the nondominant hand (Kennedy et al., 2016). Intriguingly, the way in which a performer focuses attention can derail this relationship. In a study intended to extend the comparison between the effects of attentional focus and handedness by testing their impact on the interactions between the limbs, de Poel et al. (2008) had subjects perform inphase and antiphase rhythmic BC tasks while directing attention to either limb, and mechanical disturbances determined the degree to which the limbs were influenced by one another. The study uncovered that the effect of the dominant limb on the nondominant limb occurs most when performers play fast or offbeat. More importantly, this effect can be reduced by directing attention to the nondominant limb. Though Amazeen et al. (1997) found that focusing on the dominant hand can decrease variability in planar oscillations of handheld pendulums, this type of movement is far removed from polyrhythmic striking.

Regardless of which limb receives attention, the playing height tends to increase for that limb (de Poel et al., 2008). This height increase has the potential to complicate matters in the practice room because the hand playing a higher dynamic (greater force) tends to lead the other hand (Hoyer & Bastian). Derailment into a cycle of ever-increasing dynamics can easily occur since the changing of dynamics in one hand causes similar changes in both hands (Buchanan & Ryu, 2012), but dynamics are not the only consideration. Similar to force, faster hands tend to lead slower hands (de Poel et al., 2008). Peper et al. (1995a) attempted to determine the effects of tempo and role on the coupling between two hands in a BC task using five right-handed percussionists. Subjects performed a 2:3 polyrhythm tapping task at various tempos with both hand arrangements, and the results showed that the slow hand is not a good anchor point for accuracy. Further complicating matters, Sisti et al. (2011) showed that error is more likely if the nondominant hand is faster. It seems that the ideal scenario would be one in which the nondominant hand is required to play at a slower speed and softer dynamic, with few-to-no adjustments. In this scenario, the performer might trust the dominant limb to act as an anchor, instead focusing attention on the interleaving of the nondominant limb.

Imagine a scenario in which a right-handed performer must learn a 5:7 polyrhythm where the faster rhythm (7) is played at *piano* with the left hand and the slower rhythm (5) is played at *forte* with the right hand. Multiple discrepancies arise because it is not at all clear which limb should receive attention. The left hand could be the anchor because it is faster, but it suffers from playing at a softer dynamic. The right hand could be the anchor because it is playing at a louder dynamic, but it suffers from being the slow hand. It may seem obvious to use dominance as a tiebreaker, but the reality is that even this situation neglects to account for task-switching. In any genuine complex BC performance situation, the task requirements far exceed the simplistic relationships outlined between handedness and role. Attentional demands are in constant flux, and making such determinations in real time is not feasible. By stepping away from purely external objects of focus and toward internal perception, a new selection of tools emerges to aid in the performance of polyrhythms.

Internal and External Perception

It can be difficult to imagine the difference between internal and external perception. A relatable example may be the visualization of scenes in a book as opposed to recognition of the shapes of the letters on the page. While this process is not exactly what takes place during BC, it succeeds in highlighting the human ability to focus inward and outward. Internal and external information are provided by the nervous system all of the time, and the prioritization of this information through perception has a major impact on performance. Perception is central in developing a unified protocol for each coordination task, understanding the relationship between the nervous system and sensory FB, and monitoring for error correction. Addressing the characteristics of these internal and external states will help to illuminate the importance of perception in the learning of bimanual skills.

The first perceptual task is to form a general conceptualization of the BC pattern. The bimanual skill can be perceived as either an integrated set or various component parts. Klapp et al. (1998) argue that bimanual rhythms must be learned as an integrated set and that it is "essentially impossible to achieve independence in human bimanual action" (p. 316). There seems to be practically no overlap in these modes of task perception as the same study showed that learning the integrated rhythm does not aid in performing the component parts. Described before in terms of goal-orientation, unified perception is beneficial to the execution of a bimanual task (Oliveira & Ivry, 2008). Taking it further, Diedrichsen et al. (2003) conclude that coupling presents at early stages of learning based on the manner in which actions are represented. Perception, then, is at least partially responsible for mitigating errors due to the mirroring of limbs.

The same year, Hodges et al. identified perceptual difficulties in discriminating the required movement in complex BC patterns, likely related to perception of the task as a whole. Likewise, Michaels et al. (2017) identified a noise component to the learning process, labelling intention as critical for addressing independent aspects of bimanual skill. Investigating the effectiveness of receiving perceptual experience of a polyrhythm during motor practice of the unimanual parts of the polyrhythm, Kurtz & Lee (2003) had 36 subjects randomly assigned to three practice groups: one practiced both parts of a 2:3 polyrhythm with both pacing tones, one practiced each rhythm separately with its corresponding pacing tone, and one practiced each rhythm separately with both pacing tones present. While practicing the full polyrhythm was indeed best overall, polyrhythmic structure was facilitated when training included the aural presence of the whole perceptual polyrhythm despite practicing the rhythms independently.

Here, the power of perception compensates for poorly designed practice. It is abundantly clear that learning BC patterns necessitates a unified perception of the pattern and does not benefit in the slightest from the learning of component parts.

While abstract, perception is rooted in the nervous system. Debaere et al. (2003) found different areas of the cerebellum were activated depending upon whether guidance was internal or external. The study showed that there are distinct neural pathways for externally and internally guided cyclical bimanual movements. Temporal interactions such as BC reflect the behavior of a unified timing representation[83] (associated with the cerebellum), and many of the constraints underlying BC are divorced from processes surrounding motor execution, instead arising at an abstract level (Ivry et al., 2003). Also, through a cognitive lens, Mechsner & Knoblich (2004) explain that "movements are planned, executed, and stored in memory by addressing their anticipated, mentally represented, perceptual and conceptual effects," typically disregarding necessary muscular patterns (p. 501). They also argue that perceptual anticipation of the effects of movement are functional in organizing the corresponding movement, and this very anticipation is a pivotal step in the acquisition process. Despite its importance in the learning stage of bimanual skills, perception is not the main influence on crosstalk between the limbs (Kennedy et al., 2013).

Beyond a general conceptualization of BC tasks, perception is fundamental to the process of monitoring. The cognitive monitoring of specific notes has been found to occur maximally at around six notes per second (Bogacz, 2005). Given this criteria, in a 5:3 polyrhythm, the faster hand would be playing at a speed of 360 notes per minute. After this point, perception of individual notes dissipates, and it seems to place a cap on the size and rate of discrete units processed by the brain.[84] Perception negotiates sensory input as well. For instance, the perception of movement direction can modulate the learning of a bimanual skill (Brandes et al., 2017). This perception can be internal or external, relying on proprioception or sensory input in the form of auditory or visual information. In terms of external perception, auditory information regarding direction of movement is provided by the sound of wooden or metal bars on a keyboard percussion instrument (rises in pitch frequency indicate movement to the right). Visual information about direction of movement is provided either directly or through peripheral vision. Internal perception relies heavily on proprioception, and this sense of one's limbs in space is utilized heavily in keyboard percussion playing because the instrument is often too large for

[83] For a definition of *representation*, see Appendix B.
[84] For a table of cognitive tempo thresholds for specific hand speeds, see Appendix C.

both limbs to be viewed simultaneously. While Brandes et al. (2017) found that BC is guided by both proprioception and visual information, visual information is disregarded for anatomical information as long as it matches proprioceptive FB.[85] In the hierarchy of perceptual importance, internal proprioceptive focus seems to be at the top, and it may be the key to successful bimanual performance. The observed consequences of the action are then integrated into the representation of the action that caused them (Diedrichsen et al., 2003), meaning the perception of an action includes the constant assimilation[86] of experiential information, and it refines itself accordingly.

In conclusion, determining internal or external focus is critical in the learning of a complex bimanual skill (Shea et al., 2016). Rather than learning limbs independently or thinking of BC tasks as combinations of discrete limb movements, a default mode procedure (also called a control policy) must be learned that relates each limb to the other (Yeganeh Doost et al., 2017). This procedure is a coordination template, and it doesn't contain specific muscle movement information. Instead, it relies on perception. Promoting the internal generation of movement is helpful for two reasons: proprioception may be dominant over vision in bringing about synchronization (Mechsner & Knoblich, 2004), and guiding movement with an internal perception can be a helpful strategy when the input for externally guided movements is disrupted (Debaere et al., 2003). Implementing this internal perceptual framework is best done from the very beginning, as most early-stage learning is due to practicing the control policy and not the specific sequence of bimanual tasks (Yeganeh Doost et al., 2017). Error detection and correction do benefit from sensory input, but a reliance on proprioception is critical. The literature on perception paints a picture of BC as a process of generating singular internal templates for complex actions that can be tested against external stimuli and continually reinforced from within. In practice, this procedure is not terribly difficult to implement.

Internal and External Perception in the Percussion Practice Room

It is clear from the research that a unified representation of the BC task is necessary (Ivry et al., 2003; Klapp et al., Kurtz & Lee, 2003; 1998; Oliveira & Ivry, 2008; Yeganeh Doost et al., 2017). This composite rhythm serves as a control policy, and the individual muscle movements for polyrhythms exist beneath the umbrella of this control policy. Using this method, a percussionist might learn a composite rhythm of one quarter-note, two eighth-notes, and one

[85] For more information on the relationship between vision and proprioception, see *visual capture* in Appendix B.

[86] For a definition of *assimilation*, see Appendix B.

quarter-note. They would then learn the rhythm (either physically or mentally) with hands in the following order: both hands, right hand, left hand, right hand. This is the control policy for a 3:2 polyrhythm, and knowledge of the frequency ratio is unimportant for the learning of the task. While it may be useful to anchor timing with the fast hand (Klapp et al., 1998), it is important not to rely too heavily on external stimuli for FB during the early stages of learning. Strengthening internal perception may be helpful for preventing errors due to visual FB (Debaere et al., 2003), and this perception of limb motion seems to be prioritized over visual information anyway (Brandes et al., 2017; Mechsner & Knoblich). Though external stimuli indeed help with error correction, requiring a shifting of focus between aspects of the skill to address specific issues (Michaels et al., 2017), ultimately, it may be best to move toward a complete internalization of the polyrhythm (Shea et al., 2016).

Developing an optimal perceptual framework is not without its challenges and can be thought of as its own separate task. Viewing a demonstration of a polyrhythm is not enough to be able to replicate it because the perceptual framework has yet to be developed (Hodges et al., 2003), and the listener's perception is completely distinct from the performer's perception. For the same reason, practicing slowly does not aid in fast BC, and attempting to think about fine details during fast BC can actually be detrimental (Bogacz, 2005). The perception of the polyrhythm, ideally informed by its control policy and reinforced primarily through proprioception, cannot be the same at fast tempos. In these instances, a new control policy would need to be developed. This concept extends to direction of motion as well. The control policy for a 3:2 polyrhythm, played on pitches F and C of a xylophone, will not work for a 3:2 polyrhythm in which one of the hands remains on pitch F and the other alternates between pitches C and D. Two new control policies would need to be learned in this scenario; one in which the moving hand begins on C and another in which the moving hand begins on D. These additional steps are partially the result of learning new muscular patterns, but perception is a major obstacle to skill transfer as the mind is required to set up discrete conceptualizations for each individual pattern.

The development of a comprehensive system for polyrhythmic learning seems necessary when confronted with implications from the BC literature on perception. Error is more likely when a limb is playing slower, softer, or moving less. The complete task should be attempted at the outset of learning. By extension, sticking adjustments (right or left) do not aid in the learning of a polyrhythm. Perception of coordination based on the composite rhythm is key. Directing attention to the nondominant limb can reduce some of the negative effects of handedness, but a limb that receives attention will increase in playing height. Faster, louder hands tend to lead, and the slow hand should not be the primary anchor point for time. Tasks must be represented as a unified whole, and external stimuli should not be relied on too heavily during early learning stages—task internalization is the end goal. Practicing slow does not aid in fast playing, and attempting to think about fine details can be detrimental. Perception is integral to the uniqueness of learning polyrhythms, and it forms the core conceptualization of the new pedagogical structure. Implementing this conceptualization requires the creation of tools specifically catered to polyrhythms, and the necessary components can be found in the BC research on FB.

Chapter 3: Feedback and Bimanual Coordination

In order to form a perceptual framework for a complex coordination pattern, *understanding* of the pattern must be cultivated and internal focus must be trained. Throughout the early stages of the BC learning process, important external sensory information is provided through sight, hearing, and touch. These senses help to determine the placement of playing implements, such as mallets and sticks, the force of a stroke, and timing accuracy. The nervous system uses this sensory input and is sensitive to input that receives attention. Various stimuli can attract attention, and since attention is the conduit through which perception is mediated, FB is a critical facet of perception. For example, Bogacz (2005) showed that auditory and visual FB are mediated by temporal focus of attention, and FB is global instead of detailed at high speeds. Importantly, FB is not merely sensory information; it is salient sensory information pertaining to task performance. The brightness of the sun through a window is indeed visual input, but it is not FB regarding bimanual performance.

The primary forms of FB for complex bimanual skills are visual and auditory FB. These modes of FB are critical in the learning of most motor skills, but the role they play in BC is uniquely important. Because of this role, FB needs to be curated to fit the goals of practice and keep from inhibiting progress by confusing the performer's perceptual framework. It also must be approached with caution, as performers can become overly dependent on certain forms of FB (Sisti et al., 2011). While it is true that haptic[87] FB plays a minimal role, there is no clear evidence that the brain optimally integrates bimanual information about object curvature, and the redundant information provided by two hands does not benefit haptic information (Squeri et al., 2012).

[87] For a definition of *haptic*, see Appendix B.

To better utilize FB, it must be understood in terms of its component parts, their uses and drawbacks, and the way in which FB relates to other critical variables surrounding BC. FB is an inevitable component of the learning process, and its value as a potential tool cannot be overstated in the journey to develop a more thorough approach to the learning of complex polyrhythms. Vision is the FB mechanism most closely related to the medium through which polyrhythmic information is initially conveyed to the performer.

Visual Feedback

Intentional or not, visual information seeps into the learning process. BC is particularly sensitive to changes in perception, and visual information can easily cause these changes to occur. This type of sensory input is useful for determining the location and directionality of the limbs. While proprioception can help with the same thing, visual information is specifically important for percussionists. Since percussionists regularly play on novel instruments and instrument collections, visual information is paramount if only to aid in the transition to proprioceptive guidance in novel practice scenarios. Beyond locating the limbs and detecting the reason for error, music notation provides visual instructions and suggestions for performance. Metronomes that include a visual component such as a blinking light or pivoting arm provide important timing information used for error correction, and videos are often used for modeling and self-reflection. These types of visual FB are passive, unrelated to the activity of the performer in real time. Research has shown a unique connection between BC and visual FB that is outfitted to reflect the specific task at hand. In order to manipulate visual FB into a usable practice tool, it is necessary to understand its general effects, benefits, and deficits as well as its relationship to haptic information, handedness, and proprioception. Visual FB is one of two major FB systems that comprise the sensory input facet of the optimal learning process for polyrhythms, and it is possibly the most readily available and difficult to control.

Visual information provides FB through the nervous system that can aid in error correction, but it does not provide enough information to be the sole stimulus utilized in BC. Temporal and spatial parameters are affected by visual FB (Weigelt & Cardoso, 2003), and while corrections in isometric force production are driven in large part by visual information in symmetric movement, there seems to be a particular level of visual gain that optimizes performance (Hu & Newell, 2011).

It is clear that visual FB affects BC, and some of these effects may prove beneficial to the learning process. For instance, task performance often improves with more visual information (Hu & Newell, 2011). Not all visual information is treated equally though. When this information provides FB about relative velocity in real time, it is easier to approximate the required frequency ratios quickly and effectively (Boyles et al., 2012). Similarly, visual information providing FB about pursuit tracking results in better BC learning with FB present (Hurley & Lee, 2006). Visual FB seems to be generally helpful for highly complex BC tasks if the visual pattern is simple enough (Hu & Newell, 2011). Given the difficulty of controlling visual space in a typical learning environment, visual complexity is bound to arise.

Complexity in visual sensory input may detract from task performance, indicating a potential deficit of visual FB. Weigelt & Cardoso (2003) argue that at least some bimanual interference occurs due to external FB. Since interference is a primary culprit for the coupling of limbs, it is safe to assume that excess (or inappropriately channeled) visual FB can be problematic in the early learning stages in which decoupling the limbs is a high priority. Additionally, the benefits to the learning of BC due to visual FB often deteriorate once removed (Ronsse et al., 2011). It is difficult to make the case for a visually rooted FB system when retention is not guaranteed. In a perfect scenario, the visual FB would remain constant throughout all learning and performance stages, but the implementation of such a system is unrealistic.

The effects of visual FB can change depending on haptic information, handedness, and proprioception. Amazeen et al. (2008) found that performers use visual and haptic information about limb movements, so the effects of visual information are not isolated in typical performance scenarios. In some cases, higher visual information only affects force output in special circumstances, such as when the dominant hand contributes more force (Hu & Newell, 2011). While proprioception has been discussed in terms of internal perception, it interfaces with visual FB, and there is significant overlap of sensory input. Proprioception and vision have different estimation precision in body localization,[88] and attention influences the integration process (Hu & Newell, 2011). The relationship between these two modes of FB is analogous to the relationship between internal and external perception whereby visual FB is reinforced by external perception and proprioception is reinforced by internal perception. Furthermore, visual FB inhibits the development of proprioceptive coordination (Ronsse et al., 2011), and this inhibition gets in the way of a gradual internalization of BC patterns. The case could be made that the early benefits of visual FB are outweighed by its detrimental effects to skill internalization and retention (which are undoubtedly related to one another).

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[88] For a definition of *localization*, see Appendix B.

Visual Feedback in the Percussion Practice Room

If visual FB is used to aid in learning polyrhythms, the timing of its use should be considered. According to Sisti et al. (2011), visual FB is most helpful during early learning stages. It may be that visual FB should be leveraged as a tool for understanding the polyrhythm depending on the type of tool used. A visual metronome that shows the accurate rhythmic ratio during the learning process may help to quicken skill acquisition, but attention can impact its usefulness. Focusing on the environment, for example, instead of the physical movement can aid in performance (Hurley & Lee, 2006), so any benefits may not be apparent if attention shifts away from the visual tool and toward the visual information provided by movement of the limbs.

Visual FB can aid in the learning of dynamics, but the process needs to be finely controlled. In a study examining how the influence of visual information on force coordination patterns may be dependent on task asymmetry,[89] Hu & Newell (2011) had subjects isometrically apply force with index fingers whose sum matched a target force represented by pixels on a screen. The visual information was manipulated to test the effect of visual FB, and the results showed that visual FB can aid in the learning of force production (roughly equal to changes in dynamic in a performance situation) if it is not overly complicated. In a real-world scenario, a digital audio workstation (DAW) could be used to provide real time dynamic information provided microphones were set up to accurately capture the sound of performance. In this situation, a visual representation of the sound would be indicated via waveform or decibel reading on the individual channels. To isolate the volume of each limb, contact microphones could be attached to two separate surfaces, each picking up the vibrations of one individual limb. Even still, the visual FB would represent the sound caused by variances in force, not the variances in force themselves. This degree of separation could potentially impact the effectiveness of the FB. The argument could also be made that this FB is not simple enough to be effective. Sisti et al. (2011) warn that using simple visual FB cautiously is necessary to avoid dependance on the FB, and since this particular method is not readily available in most performance situations, dependence would need to be avoided entirely.

A more common form of visual FB is video, and this tool receives ample advocacy in the music performance sphere**.** Hodges et al. (2003) attempted to determine if video FB helps to make relative phase information apparent by helping the discrimination process in the learning of bimanual skills using two groups of 10 subjects that practiced a novel BC pattern, one of which was given video FB of their own performance after each trial. They found that video FB, in

[89] For a definition of *asymmetry*, see Appendix B.

particular, is helpful for inexperienced learners and complex BC tasks, but yet again, a reduction in FB over time is recommended.[90]

Though the type of visual FB makes a difference, the way in which it is implemented may be even more important. In a study meant to determine if multifrequency continuous bimanual circling movements of varying difficulty could be effectively performed following relatively little practice when real time continuous relative velocity FB was provided, Boyles et al. (2012) had subjects perform bimanual circling movements (1:2, 2:3, 3:4, and 4:5) with visual FB that reflected correct and actual performance in real time. The study showed that when visual FB provides information about performance relative to the goal in real time, it helps to rapidly learn polyrhythms. Referred to as "augmented feedback," this method allows for immediate error correction. The benefit of augmented FB is that it has the potential to reduce the amount of incoming visual information (compared to that provided by normal self-reflective observation), instead highlighting only the most important aspects of performance. As mentioned regarding the use of a DAW[91] as a visual tool for aiding dynamics, augmented FB methods are difficult to implement outside of a laboratory. More worrisome is the fact that augmented visual FB may primarily aid performance only while it is present (Hurley & Lee, 2006).

There are several potential pitfalls to the use of visual FB. Weigelt & Cardoso (2003) attempted to distinguish between the visual and execution sources of BC through the investigation of reversal movements under different visual FB conditions. Subjects performed a bimanual task using visual FB on a monitor and FB was manipulated to reflect something other than the actual performance of the subjects. They discovered that this disagreement between visual information and the actual task can cause interference. Therefore, if visual FB is used, it must be as close as possible to an accurate representation of the task (or the performance of that task if the FB is augmented). The study also showed that timing and spatial execution are affected by visual information, which could be detrimental to performance if there is a disconnect between visual FB and the BC task. In addition to helping while present, visual FB can cause playing to degrade once removed (Gooijers et al., 2013). Lastly, visual stimulus causes over-adjustments in practice (Wahl et al., 2016). Over-adjustments can aid in the learning of a complex BC task, but they are inherently errors, so a recognition of this tendency is paramount.

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[90] For more information on the effects of observing the performance of others as opposed to observing one's own performance, see *common coding theory* in Appendix B.

[91] DAW, *digital audio workstation*. For a list of abbreviations, see Appendix A.

Despite these pitfalls, the negative consequences of visual FB may not be terribly severe. As discussed regarding perception, watching a demonstration of a polyrhythm (such as with video FB) is not enough for replication of the movement (Hodges et al., 2003), so the nervous system relies on other forms of FB even in this common scenario. Furthermore, since proprioception and haptic FB affect performance accuracy more than visual FB (Amazeen et al., 2008) and estimations based on vision are not the same as those based on proprioception (Hu & Newell, 2011), the real danger lies in the interpretation and implementation of internal FB mechanisms. These mechanisms often seem to disagree with visual FB, but this disagreement can be mitigated, even circumvented, with a different form of sensory input.

Auditory Feedback

Auditory FB encompasses the sounds produced by playing, verbal criticism, audio recordings for modeling or self-reflection, and the sound produced by metronomes. As discussed regarding visual FB, these sensory inputs are passive and lack a direct relationship to the notes being performed in real time. The benefits of metronome practice and self-reflection through audio recordings have been discussed at length in the musical literature, but the BC literature must be referenced to gain insight into the function of auditory FB in a complex bimanual learning environment. While the benefits and deficits of auditory FB are important, the ways in which it varies from visual FB provide true insight into the power of FB for the learning of polyrhythms. Auditory FB is a crucial element of the sensory input system when it comes to forming a new framework for the learning of polyrhythms, and its strength as a tool may surpass visual FB.

The general benefits of auditory FB are similar to those of visual FB, but its effects on retention are distinct and robust. According to Dyer et al. (2017b), learning is faster and more accurate with sonification. The brain areas associated with BC in the presence of auditory FB are unique. Prefrontal activations are more elaborate, suggesting stronger cognitive involvement, and auditory FB benefits remain after removal (Ronsse et al., 2011). This cognitive difference suggests that the benefits of auditory FB take root through different facets of the nervous system from visual FB, and this could be the reason for its superior effects on retention. The tendency for a performer to rely heavily on FB—and for performance to deteriorate upon its removal—is referred to as the guidance hypothesis[92] (or guidance effect), and it can be overcome with concurrent sonification during the learning of a bimanual task (Dyer et al., 2017b). Concurrent sonification occurs when sound provides FB while performing, but the sound

[92] For a definition of *guidance hypothesis*, see Appendix B.

used is just as critical as its timing. Melodic sonification, for instance, drastically improves learning and retention in complex BC (Dyer et al., 2017a). In this type of auditory FB, pitches correspond to muscle movements. The same study showed that performance ability was identical 24 hours after learning when allowed to hear the melody first. It is possible that the melodic information is incorporated into the control policy for that specific BC task. The control policy model would explain the need for a reminder of the melodic component prior to performance after time has elapsed. Despite these benefits, not all auditory FB is equally useful. The same study found that non-melodic sonic FB does not aid in learning or retention more than absent FB (Dyer et al., 2017a).

Due to its benefits for retention, auditory FB may seem like the best practice tool option, but it has its own pitfalls compared to visual FB. While attending to auditory stimulus may be less demanding than attending to visual stimulus (Peper et al., 1995b), auditory FB shows less progress at the start of learning a BC task (Ronsse et al., 2011). It is often the case that speed of learning is a high priority, so this aspect of auditory FB is problematic. Ronse et al. (2011) also showed that the visual motion area hMT/V5+ remains activated when visual FB is removed, but auditory regions deactivate when auditory FB is removed. Somehow, using an auditory stimulus acts like a training wheel that can then be removed, and the cost is a slower initial learning process. The same study determined that learning progress in the presence of auditory FB eventually reaches the same level as learning progress in the presence of visual FB, despite the slow start. Sisti et al. (2011) posit that auditory FB is better for consolidation[93] while visual FB is better for speed in learning. The usefulness of each adjusts according to the needs of the performer. Notably, auditory FB has been found recently to have no performance improvement benefits for musicians (Kuo & Fisher, 2020). Context matters of course, but training clearly influences the usefulness of FB tools.

Auditory Feedback in the Percussion Practice Room

Practice guided with auditory FB may be more beneficial to learning than visual FB (Peper et al, 1995b), and this is in part because auditory aids are better for consolidation (Sisti et al., 2011). Since consolidation is such an important aspect of the learning of polyrhythms, the performer should consider leveraging sound to ease the process. The most common example of auditory FB in the practice room is the use of a metronome, though reference recordings and personal recordings are examples as well. While the metronome does provide salient information as a timing reference, its use must be manufactured to produce the benefits seen in

[93] For a definition of *consolidation*, see Appendix B.

the scientific literature. A common analog metronome cannot produce concurrent or melodic sonification of multiple rhythms simultaneously, but some digital metronomes have this capability, and they should be seriously considered as auditory FB tools for the learning of polyrhythms.

Auditory aids are also beneficial for retention due to internalization and unified perception. In a study meant to examine the effects of augmented FB on the learning of complex bimanual skills, Ronsse et al. (2011) had two groups of subjects acquire a novel BC pattern under different conditions—visual input reflecting the coordination between two hands and auditory pacing integrating the timing of both hands—while examining via fMRI. The study showed that auditory FB promotes internalization, and the results remain when FB is removed. Interestingly, both the visual FB and auditory FB in this study promoted a unified perception of the task, but the auditory stimulus seemed to imbed that perception more accurately into current and future performance of the task. Since the benefits of auditory FB are so intimately linked to its effects on perception, it is important that performers use auditory tools that reflect a unified concept of the polyrhythm. The benefit would be lost, for example, if one limb coincided with a high-pitched metronome and the other limb coincided with a low-pitched metronome. This sonification would promote a perception of the limbs as discrete units and undercut the value of auditory FB.

The value of this FB lies in its use in tandem with the movement of the limbs. Dyer et al. (2017b) showed that auditory FB can be useful in early learning stages if it occurs while playing, so the metronome examples are readily applicable. Further, utilizing varied sounds with the auditory FB tool can be helpful. Dyer et al. (2017a) showed that melodic sonification can be a powerful tool for the quick learning and retention of difficult polyrhythms. The key would be to create a system for sonification that promotes a melodic conception of the polyrhythm without unintentionally promoting the limbs as separate entities. If melodic sonification is used, the sound utilized in tandem with the striking of both limbs should be distinct from the sound utilized for either of the limbs separately. For instance, the auditory FB tool used for the learning of a 3:2 polyrhythm might produce the pitch E for the first note (hands in unison), G for the second note (right hand), C for the third note (left hand), and F for the last note (right hand). Each movement has its own sound association, and while the raising and lowering of pitch correspond to the movement from one limb to another, these pitches do not repeat and therefore promote a unified conceptualization of the coordination pattern. Even more useful would be a system that plays those sounds while a surface is struck. Thankfully, most percussionists in academia have access to keyboard instruments. The addition of horizontal motion variables causes a problem, however, as transferring the newly learned polyrhythm to a multiple percussion setup would be a challenge. This issue can be circumvented by using an identical sound for every movement, but the potential benefits of melodic sonification will be lost.

This tradeoff could potentially be mitigated using simultaneous visual and auditory FB, but the performance environment must also be considered. The motor system clearly prioritizes readily available perceptual information, so the learning process should mirror the performance environment as much as possible (Dyer et al., 2017b). Additionally, the benefit of auditory FB diminishes with expertise (Kuo & Fisher, 2020), so it should be seen as a tool to facilitate internalization. Meanwhile, visual FB can supplement this internalization by aiding in the rapid understanding of polyrhythmic coordination. The visual aid should be removed as early as possible, and the auditory aid should be used to facilitate this transition. Whatever the case, the auditory aid should be used in the real performance environment (or something approximating that environment) before removed completely. Lastly, poor and variable performance results from attention-splitting information, possibly due to an inability to extract FB quickly or effectively enough to correct errors in real time (Boyles et al, .2012), so both forms of FB need to agree with one another. The most important consideration is that FB tools must promote a unified perception of the polyrhythm regardless of how long—and in what context—they are utilized.

Auditory FB is one part of a much larger picture regarding the sensory experience and its relationship to motor skill acquisition. The information provided in these studies is invaluable for the formation of a new method of learning polyrhythms. Visual FB is best used in the *understanding* stage of learning. Dependence on visual FB is likely if it is not simple or removed early in the learning process. Video FB is helpful for inexperienced learners, though all visual FB providing salient real time information is helpful. Augmented visual FB may only aid performance while present, and over-adjustments can result from the use of visual FB. Auditory FB may be more beneficial to learning than visual FB because it is better for consolidation and internalization even with FB removed, and this benefit relies on concurrent sonification. Melodic sonification can be a powerful tool for the quick learning and retention of difficult polyrhythms, but the learning process should mirror the performance environment. The new system of learning required by the unusual polyrhythmic learning experience would benefit greatly from the implementation of tools that reflect realizations in the FB literature. All the variables discussed thus far are integral to addressing error, but perception and FB tools can be focused keenly if typical presentations of error are exposed.

Chapter 4: Error and Bimanual Coordination

An optimal practice strategy for the learning of polyrhythms would include mechanisms to easily prevent, monitor, and address error in all stages of rehearsal. Error itself is a tool, and it provides ample information to the performer about accuracy and consistency. While the ultimate goal is to reduce error, it is a necessary component of the learning process, and its relationship to the nervous system, perception, and FB as they relate to BC is pivotal. Through error, the unique nature of polyrhythmic learning and performance will become increasingly apparent, and the necessity for a new pedagogical approach will coalesce. While error in coordination is often related to timing inconsistencies, it can also appear in force production and direction of motion. Monitoring for error as a perceptual obstacle is only part of the challenge in BC. Identifying the cause will require a closer look at the effects of fast tempos and symmetry between and within the limbs in the context of trained and untrained performers. In order to develop a new system for learning polyrhythms, the cause of error in BC must be illuminated. One of the most prominent symptoms of error is a collapse of the coordination pattern, and this collapse is often due to increases in frequency.

Frequency and Collapse

Fast tempos are a known enemy of comfortable performance. Often, this conundrum is framed as a mechanical problem, one solved by brute force methods. When fast tempos cause breakdowns in performance success, the often-recommended solution is to increase muscle strength and dexterity through repeated exposure to fast tempos. This method undoubtedly aids in many aspects of performance, but it would be unhelpful to prescribe this regimen to a student struggling with fast polyrhythms. Often, an increase in polyrhythmic frequency results in error due to perceptual difficulties, not mechanical challenges. A relatively slow hand motion can be challenging to perform when confounded with another slow hand motion that is slightly offset. Consider a 7:6 polyrhythm at 60 beats per minute. Hands at this speed are moving relatively slow, but likely, any performer learning this polyrhythm for the very first time will need to begin much slower to develop a proper understanding of the rhythmic timing ratio. As frequency increases, the ability to perceive the newly learned ratio diminishes, and the limbs are likely to drift, or collapse, into a stable rhythm. Frequency and collapse can be understood in terms of their proportional relationship and its grounding in the nervous system, their effects on movement control, and the integral nature of phase shifts and ratios. Collapse due to changes in frequency is the primary cause of error in BC, and it is the first step to addressing mistakes in a new pedagogical model.

Frequency differs from speed in that it doesn't necessarily reflect speed of motion for individual movements. Instead, frequency indicates the timing of intervals between discrete movements. Frequency can be indicated with a metronome marking, while speed often correlates with changes in volume or dynamic (faster strokes produce louder sounds on idiophones, for example). This distinction is fundamental to the cause of error because of frequency. Simply put, as the latter increases, so does the former. The reason for this correlation is rooted in the nervous system. The motor system does not adjust due to sensory reflexes as frequency increases, and some perceptual processes stop providing real time control altogether, most likely due to delays in neural signaling (Bogacz, 2005). There is a point at which brain processing cannot keep up with the rate of rhythmic performance, and while this change due to frequency has already been discussed in relation to perception, its effects on error are equally profound.

Error due to frequency presents itself in many ways, such as variability in movement control. Regarding horizontal motion, increased movement frequency can result in larger movement shifts (Buchanan & Ryu, 2006). Additionally, tension appears in the fast hand as frequency increases, no matter the absolute speed of the hands (Peper et al., 1995a). It follows that there is a tradeoff between frequency and evenness, and this may relate to the interhemispheric communication required by evenness in execution (Kuo & Fisher, 2020). The consensus is that muscle control diminishes with increases in frequency, and this mirrors the concept that the brain cannot keep up with the hands as tempo climbs. The ability to make small, frequent corrections is undermined by the speed of the rhythm, and this makes it challenging to compare slow tempo learning to fast tempo performance.

When the frequency increases to the point that the task becomes unmanageable, a collapse occurs whereby the rhythmic ratio performed incorrectly approximates the desired ratio. Phase is used to describe the relationship between limb frequency, and it can be categorized in two ways: inphase and antiphase. Inphase movement, seen in isochronous tasks (1:1), occurs when the limbs are synchronized and utilizing the same rhythmic pulse and feel. Both limbs could easily utilize the same metronome in an inphase task. Antiphase movement occurs when the limbs are asynchronous and utilize different rhythmic feels. The speed of each limb would need to be indicated with separate metronomic pulses. Common antiphase intervals used in BC studies include 3:2 and 4:3. Higher order ratios are common in the percussion literature (5:4, 6:5, 7:4, etc.). The effect of frequency on timing error can be conceptualized in terms of phase. Faster cycling frequency in BC results in increased movement from antiphase to inphase (Lee et al., 1996; Sisti et al., 2011). Specifically, the nondominant hand is more likely to collapse into inphase movement as frequency increases (Wahl et al., 2016). Since the studies on handedness show that hand role adjusts with speed differences, it may be the case that the slow hand is most likely to collapse and not merely the nondominant hand. The key takeaway is that the error produced by increases in frequency is not random. Instead, it is related to a preference by the nervous system for inphase movement.

As it turns out, the way in which collapse occurs is more nuanced than a switch from antiphase to inphase. While there is a general tendency to make errors in that particular direction, there are steps in between the desired antiphase movement and completely inphase movement. These steps are determined by ratios related to the desired antiphase ratio. This process almost seems like an attempt by the nervous system to reduce error by changing the task itself, evidenced by isochronous patterns resulting in the smallest error (Sisti et al., 2011). Specifically, there is a tendency to collapse into 1:1 and 1:2 ratios when there is an inability to perform the task (Klapp et al., 1998). Examining more closely, this tendency seems to be a collapse into the nearest lower order ratio when the task becomes too difficult (Peper et al., 1995b). This nuanced collapse is likely to occur prior to a complete disintegration into inphase movement, and knowledge of this tendency can aid in error detection and prevention. An additional implication is that comfortability with a variety of bimanual rhythmic ratios would increase the number of possible collapse ratios. An argument could be made that this increase in possible modes of error might benefit live performance by reducing the probability of complete collapse to inphase movement.

Frequency and Collapse in the Percussion Practice Room

It is not a novel concept to performers that high tempos lead to instability (Peper et al., 1995b). The form of that instability, though, is distinct for polyrhythms. Instead of general shakiness in timing or rhythmic stuttering, polyrhythms tend to devolve into different, yet stable, rhythms. The most stable bimanual pattern is any in which the hands play in unison, and faster speeds tend to cause polyrhythms to collapse into this pattern (Wahl et al., 2016) or a different nearby polyrhythm (Peper et al., 1995b). For example, a 7:4 polyrhythm may collapse into a 6:4 polyrhythm (which feels like 3:2) at fast speeds because a 3:2 polyrhythm is more stable and may feel more familiar to the performer. Likewise, a fast 3:2 would likely collapse into a 1:1. This unison rhythm might appear in an alternating format whereby the limbs are rhythmically identical but offset by one unit. Said another way, in typical music notation, a triplet played with one hand and eighth notes played with the other simultaneously would likely collapse into alternating sixteenth notes.

The timing of movement execution is not the only parameter affected by greater frequency. Cyclic motion in BC becomes unstable when playing speed increases (Buchanan & Ryu, 2006). This type of motion is utilized in the playing of maracas or shakers when sustain is indicated. Brushes often use a cyclic motion, and the horizontal movement around a multiple percussion setup can sometimes resemble a circle. In these performance scenarios, greater speed will increase the likelihood of a collapse to inphase movement. Movements similar to a doorknob rotation are also susceptible to error because of frequency increases (Sisti et al., 2011). These motions are used for frame drums with jingles (tambourine, pandeiro, etc.), cabasa, and four-mallet keyboard techniques. While it is unlikely that a percussionist might need to play two different rhythms with two tambourines at the same time, polyrhythms are common in the keyboard percussion literature. To make matters worse, tension increases with frequency as well (Peper et al., 1995a). All of these various performance situations require a high level of muscular control that is undermined by increases in tension.

Since the brain negotiates BC demands completely differently once frequency increases past a certain threshold (Bogacz, 2005), the primary consideration when tackling errors due to increases in speed is picking the correct tempo during practice. Reducing tempo, a common problem-solving technique, will not produce the desired results with BC. Playing a polyrhythm slowly and correctly does not lead to better antiphase performance at fast speeds. Slow practice may indeed aid in *understanding*, but this is a separate awareness process. The solution may be repeated brute-force attempts to perform the polyrhythm at the desired tempo. “Chunking” strategies (separating motor tasks into smaller units) may be useful to reduce physical and cognitive demand until correct repetitions materialize, and endurance may increase with the gradual addition of larger chunks. Issues in timing, tension, and direction of motion in high frequency BC tasks should be addressed near the desired target tempo to ensure improvement in the specific motion required by the task. Even if these issues are addressed as recommended, errors may still arise due to less-controllable matters of symmetry and physiology.

Symmetry and Physiology

While physiology[94] is concerned with the way in which a body part functions, symmetry is concerned with the relationship between the physiology of multiple limbs. Physiology is

[94] For a definition of *physiology*, see Appendix B.

helpful for understanding the way wrist motion facilitates the striking of a playing surface, and symmetry can help explain why movements with identical rhythmic structure can become challenging with changes in direction of motion. In percussion performance, symmetric movement is rare. Occasionally, the limbs may move inward toward the body simultaneously, such as on a multiple percussion setup or a keyboard instrument. And while playing on a snare drum requires identical movement types from each hand, the implements rarely strike the surface simultaneously. The discussion about symmetry and physiology in BC spans the nervous system, muscular relationships, the difference between symmetric and asymmetric tasks, and inherent physiological biases. The likeness of muscle movements between limbs during BC has repercussions for error and its incorporation into a novel system for learning polyrhythms.

Symmetry can refer to the relationship between muscle groups, but it does not seem important for muscles to be similar, or homologous, to effectively perform bimanual tasks. According to Mechsner & Knoblich (2004), the homology of active muscles plays virtually no role in defining coordination patterns. This may result because of the effects of perception on BC. The same study showed that the tendency for muscles to mirror one another is independent of finger combination. The implication is that coupling must originate on an abstract, perceptual level during anticipation of the consequences of movement.

In addition to muscle homology, symmetry can refer to direction of motion. Symmetrical movements are facilitated when the contralateral and ipsilateral signals are integrated while asymmetric movements suffer from errors due to conflicting information or the mixing of signals controlling the two arms (Kennedy et al., 2015). These signaling idiosyncrasies have already been discussed regarding IHI and neural crosstalk, but the relationship between crossed and uncrossed pathways to symmetrical and asymmetrical movement is integral to understanding the challenges associated with symmetry in the learning of a bimanual skill.

Symmetric and asymmetric movement result in varied BC outcomes. Asymmetric tasks lead to more variable circling frequency, dispersion of phase angle, and spatial error (Kagerer et al., 2003). Conversely, mirror symmetric (inward and outward) motions are highly stable (Sisti et al., 2011), and movements initiated in the same direction have reduced reaction times (Kennedy et al., 2013). Musical training and task type cannot be discounted, however, as differences in task performance due to symmetry are not always profound (Kuo & Fisher, 2020). It seems that novel tasks are generally easier to accomplish when required movements are symmetric, particularly if they mirror each other. Since one of the primary results of error is limb coupling, it follows that tasks requiring coupling from the outset are more manageable for the performer.

Lastly, asymmetries exist on the level of muscle contraction. Flexion (palm toward the arm) and extension (back of hand toward the arm) are opposite movements and could be considered asymmetric. Flexion muscles assist in pronation[95] (rotating the wrist inward), and extension muscles assist in supination[96] (rotating the wrist outward). The neural circuitry for flexion is more robust, therefore pronation endpoints are more consistently regulated during motor coordination (Byblow et al., 1994). At the most basic level, this thinking suggests that the body has a bias for the points in a movement that exhibit maximum flexion and pronation, but a complete conceptualization would account for the effects of perception and FB.

Symmetry and Physiology in the Percussion Practice Room

An ideal percussion performance scenario, in terms of symmetry, would be one in which both limbs move in the same direction at the same time, such as repeatedly playing a perfect fifth interval on a vibraphone. The potential for error diminishes because the direction of movement has a large impact on bimanual skill interference (Kennedy et al., 2013). The fact that similar muscle groups are utilized in this scenario is also helpful because the mechanisms that cause interference in the brain are different depending on which muscles are used (Kennedy et al., 2015). If the vibraphone player were required to shift pitches (but still allowed to move hands in unison), the next best scenario would allow for movement toward and away from the body with both hands simultaneously. In the key of C major, this movement could be achieved by alternating between G and A in the right hand and C and B in the left hand. No matter the musical quality of this sequence, symmetry is achieved in direction of motion.

These mirror-symmetric motions are highly stable (Sisti et al., 2011). If instead the left hand alternated from C# to C natural, the movements from hand to hand would become asymmetric. These types of tasks are more variable (Kagerer et al., 2003). While the vibraphone example is functional, it does not illustrate the extremes in asymmetry often required of percussionists in multiple percussion setups. Instead, imagine that one hand must alternate between swirling a brush cyclically on a tom-tom and striking a gong with a triangle beater held in the pinky while the other hand plays a melody on a xylophone. Even if the rhythms are rudimentary, the asymmetry of the task significantly compounds the difficulty of the challenge and increases the likelihood of error. Performance is easier with similar muscle groups moving in similar ways (Brandes et al., 2017).

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[95] For a definition of *pronation*, see Appendix B.
[96] For a definition of *supination*, see Appendix B.

The prescription for the malady of asymmetry may reside in muscular contraction. Wrist flexion and pronation specifically can be leveraged to aid the BC process even in asymmetric tasks. Flexion in the wrist occurs when an implement strikes a playing surface. Extension, on the other hand, occurs when an implement is lifted in preparation for another strike. These same muscles aid in wrist rotations: flexion muscles aid in pronation and extension muscles aid in supination, readily applicable to four-mallet keyboard performance. Pronation occurs when an inside mallet—mallet two or three, held near the thumb—strikes a playing surface. Supination occurs when an outside mallet—mallet one or four, held near the pinky—strikes a playing surface.[97] Checkpoints for timing accuracy in BC may occur during wrist flexion and pronation (Byblow et al., 1994).

In many situations, it is already common sense to align movements based on the timing of the striking of implements. However, when rotational movements are involved, there are specific points in rotation that should receive preference when monitoring for error. A general rule would be to anchor timing to movements that occur inward, toward the body. These movements are likely to be pronation movements, and all other typical playing motions utilize flexion. Some very specific instances exist that would benefit from anchoring[98] to flexion motions. For example, when playing tambourine with the fist-knee technique—whereby one hand flexes the wrist to strike the tambourine against the knee and extends the wrist to strike the tambourine against a fist opposite the knee—the percussionist may benefit from anchoring timing to strikes on the knee. These suggestions extend to the performance of polyrhythms which, due to the massive cognitive demand, can particularly benefit from the anchoring of timing to flexion and pronation movements. While symmetry and physiology are essential for navigating error in BC, training provides much-needed contextual information about a performer's ability to utilize these tools.

Training

Common sense would lead anyone to believe that a practiced musician should learn a musical task faster than a nonmusician. This conclusion is sound, but it is not always the case. There is no readily identifiable rhythmic similarity between a 7:6 and 15:13 polyrhythm, so determining the effectiveness of prior musical training on the learning of one of these polyrhythms is problematic. Training can have a subtle effect in this instance, but likely, a group

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[97] In four-mallet percussion playing, each mallet is labelled numerically from left to right from the performer's perspective.

[98] For a definition of *anchoring*, see Appendix B.

that has learned the 7:6 polyrhythm would struggle just as much with the 15:13 polyrhythm as a group that hadn't learned the 7:6 polyrhythm first. Despite this frustrating outcome, the case cannot be made that training is completely useless. The type of training utilized must be reframed; The system of learning must receive focus rather than the polyrhythm itself. In this chapter, the concept of training is analyzed from the perspectives of the nonmusician and the musician with suggestions for practice that illustrate fundamental differences between typical music training and BC system development. In an attempt to address error for the formulation of a new polyrhythm practice regimen, training must be discussed as it pertains to potential differences in approach relative to experience.

As explored regarding brain structure, musical training has some impact on BC. It is worth examining bimanual skill acquisition in untrained subjects to parse through the potential benefits of long-term BC exposure. One of the primary methods for tackling neural crosstalk with the aid of IHI is the interleaving of the slow hand into the fast hand. Nonmusicians, however, struggle to interleave slow taps into fast taps in the same way that proves beneficial to musicians (Peper et al., 1995a). This difference suggests that training develops the ability to learn, and this ability may increase acquisition speed, but it does not imply that skills transfer between each BC pattern. Despite this coordination deficit, nonmusicians are able to train themselves to resist phase transitions when directed to do so (Lee et al., 1996). Apparently, even after collapse begins, antiphase movement can be maintained with enough persistence. As far as external stimulus is concerned, inexperienced players benefit more than experienced players from video FB (Hodges et al., 2003). It is possible that experienced players are better at gleaning salient information from each repetition in real time thus reducing video FB to redundancy.

The brain areas associated with BC in musicians and nonmusicians are structurally distinct. Environmental influences, such as musical training, at specific developmental stages trigger structural changes reflected in FA (Johansen-Berg et al., 2007). It would be reasonable to conclude that trained musicians have an extreme advantage over untrained subjects, and while this may be the case for many musical tasks, it is not the case for BC. Though interleaving may be slightly easier with training, the fundamental truth of independence (or a lack thereof) levels the playing field. According to Bogacz (2005), true decoupling of the limbs does not occur even with training. The study goes on to criticize traditional piano instruction for aiming to teach independence of the hands, an impossible feat. Furthermore, learning a new bimanual task overshadows any benefit of previous learning (Hurley & Lee, 2006). If each novel bimanual skill introduces such a cognitive challenge to the learner that no previous BC learning is apparent, then it would prove challenging to distinguish between musicians and nonmusicians in any case without scientific measurement. BC is an equalizer, and this equalization has tremendous implications for pedagogy.

Training in the Percussion Practice Room

There are very few accommodations that should be made for inexperienced players that should not also be incorporated into the practice regimen of experienced players when it comes to complex BC. Regarding tools, video FB is particularly useful for inexperienced players (Hodges et al., 2003). Otherwise, it is crucial for inexperienced players to resist collapse of the polyrhythm into inphase motion, specifically as speed increases (Lee et al., 1996). The act of resistance is a skill on its own, and this skill should be prioritized in inexperienced learners. Teachers must recognize that students will have highly variable levels of learning and retention depending on the strength and directionality of neural connections in specific areas of the brain influenced by prior exposure at key ages (Johansen-Berg et al., 2007). Students may not know that certain experiences predispose them to learning BC skills (dance, sports, martial arts, etc. are all potential contributors). Whatever the case, skill transfer for polyrhythms is virtually absent (Hurley & Lee, 2006), so even this slight advantage will not compensate for the challenge presented by novel bimanual movement patterns. Improving at polyrhythms is not a matter of learning all the possible hand combinations and force distributions; It is a matter of learning a system to approach new situations. Early bimanual training should look like system-building instead of note-learning, and students with a predisposition for BC and trained musicians may implement this system with ease.

In a study meant to determine if speed affects the performance of polyrhythms by causing the perceptual-motor system[99] to adopt different modes of operation at different speeds, Bogacz (2005) had nine pianists memorize and perform polyrhythms over a range of speeds using several fingers in each hand. The study argues that performers should practice musical passages at the speed they plan to use in performance, recommending slow practice for *understanding*. The study also suggests that performers should not visualize or think about every note at fast speeds. These suggestions may seem like attributes of an experienced performer, but they highlight a core aspect of bimanual skill learning; The system used to learn polyrhythms must approximate performance. Many skills require a slow and steady buildup (breaking down rhythms into component parts, utilizing various subdivisions with a metronome, gradually

[99] For a definition of *perceptual-motor system*, see Appendix B.

increasing tempo, etc.), and this process becomes quicker with musical training. When a polyrhythm is the task, that process is useless, and prior training is virtually irrelevant.

An examination of musical experience in the form of bimanual training gives rise to several recommendations. To start, it is important to pick the correct tempo, and playing fast, error-prone repetitions may be an integral part of the process. Wrist flexion and pronation may be the best guide points for timing. Resisting antiphase collapse is a skill, and this skill is crucial for inexperienced learners. Lastly, there is a negligible amount of skill transfer for polyrhythms, and the system used to learn polyrhythms must be as close as possible to the actual performance environment. Training is the final variable upon which the brain's novel facilitation of polyrhythmic learning depends, and its exploration allows for a rethinking of the current pedagogical approach. Getting a sense of the current landscape of polyrhythmic thought in the percussion sphere will lay the foundation for this new system of learning.

Chapter 5: Polyrhythms in the Percussion Literature

Henry Cowell (1996)[100], well known by percussionists for his mentorship of John Cage and Lou Harrison, outlined a methodical approach for understanding and notating various rhythmic ratios in his *New Musical Resources*. Modern approaches do not deviate significantly from Cowell's methods, and they often involve the use of graph paper and least common multiples (LCM) to determine the precise relationship between two tuplets. The LCM is used to determine the appropriate number of subdivisions for the entire polyrhythm. For example, a 3:2 polyrhythm has an LCM of six, thus six discrete units of time are necessary to perform the rhythm. Since the fastest hand is the better anchor point for timing according to the BC literature, meter should be determined with hand speed in mind. A time signature of three beats in which the quarter-note receives the beat will facilitate all six subdivisions and promote the fast hand as the anchor point. Many of the articles suggesting methods for practicing polyrhythms reiterate this conversation put forward by Cowell.

In other popular books, practice recommendations are relatively haphazard when compared to the BC literature. Kish (2017) recommends slow practice, "slower is faster" (p. 41), and learning material with the hands separated, "one hand chunking" (p.25), before combining them together again. While the section on blindfolded practice agrees with the BC literature on perception (p. 34), the other two concepts disagree fundamentally. The tools mentioned by Kish likely have merit in some contexts, but this disagreement highlights the unique nature of polyrhythmic learning. Schutz (2016) writes about the scientific research on movement and

[100] The original date of publication for Cowell's *New Musical Resources* is 1930.

explains that moving along with music improves timing. Schick (2006) describes a method of conceptualizing fast polyrhythms as inherently harmonic, echoing sentiments found in the writings of Cowell and implemented literally in the music of Karlheinz Stockhausen. While polyrhythmic harmony is indeed perceptible, it is impossible for a human to play at the speeds necessary for rhythm to become pitch. The tuning of the drums in the piece mentioned by Schick may aid in this perception though, and the idea that perception plays a key role in the performance of polyrhythms—at speeds in which thinking about the individual notes is harmful to performance—agrees spectacularly with the BC literature.

In Chaffee (1976), polyrhythms are introduced near the very final pages of the book. They are written as various tuplets in one hand against two or three beats in the other hand. The earlier portion of the book prepares the student to read tuplets in various contexts, but this transition to polyrhythms is likely to be a significant challenge because of the notation. Magadini (2001) provides a comprehensive method for polyrhythms that includes descriptive annotation for pulse, subdivision, and beat groupings. However, the tuplets are notated in such a way that the composite rhythm is not apparent, and perceptual unification is unlikely. Harrison (1999) introduces polyrhythms briefly by attaching coordination patterns to various tuplet partials. Though accurate, this method is cumbersome.

Cangelosi (2017) uses a novel notational style to indicate direction of motion. This book would be particularly useful for learning directional variations of polyrhythms that are already comfortable on a single playing surface. The visual information is simple and useful. Albright (1997) provides an in-depth guide to figuring out polyrhythmic relationships, but the polyrhythms are used as a vehicle for learning various tuplets in different meters. Chapin (2002) provides a notational system for learning coordination patterns that emphasizes the composite rhythm by distilling pattern down to the hand movement. One hand is notated above the staff line; the other hand, below. The actual musical passage appears next to the condensed version for reference. Polyrhythms are not explicitly addressed in the book, but the notational system agrees with aspects of the visual FB research regarding bimanual skill acquisition.

Beyond books and sheet music, articles about coordination, perception, FB, and cognition provide plentiful information about polyrhythms in the percussion domain. Polyrhythms in the percussion literature are often treated as novelties, and this unintentional neglect has left major gaps in the current approach to learning and teaching these unique figures. The first glance at percussion articles is directed toward coordination.

Coordination and Polyrhythms

The bulk of percussion writing on polyrhythms includes suggestions for coordination and the initial stages of *understanding* polyrhythms. Polyrhythms have slowly crept into percussive minds in the last several decades, and the way they have been envisioned has ebbed and flowed. In an article exploring the state of polyrhythms in musical literature and their trajectory in the performance landscape, Prebys (1971) criticizes music theory books for not covering odd meters in depth, credits Hindemith's *Klaviermusik* with the most revolutionary innovation of polyrhythm through syncopation, and suggests that the problem of unfamiliarity with odd meters could be solved by teaching in a progression of meters but admits that there is not enough musical literature to support it. Magadini (1973) credits the music of Africa, India, Java, and Bali with early utilization of polyrhythms as well as Charles Ives, Igor Stravinsky, Elliot Carter, John Coltrane, and Elvin Jones specifically. The article explains that contemporary composition and jazz require performers to learn polyrhythms. It is unlikely that the landscape changed drastically in two years' time. Instead, Magadini highlights a flaw in Prebys's reasoning by suggesting a need for polyrhythmic education. Additionally, the article distinguishes between *polyrhythm* and *polymeter*, correctly defining each and criticizing the lack of clarity in the literature. Like the adoption of the term *vibraphone* to mean *vibraharp*, *polyrhythmic* remains the prominent terminology for *polymetric* coordination.

Since 1973, the amount of literature supporting the learning of complex meters has increased tremendously, particularly in percussion composition, yet the pedagogy has not adjusted in an equally significant manner. By the mid-1990s the importance of polyrhythms was no longer disputed, but the proper conceptualization was still under scrutiny. Moore (1996) suggests using the term "with" instead of "over" ("3 with 4 polyrhythm" instead of "3 over 4 polyrhythm") to emphasize equality between the two rhythms. The emphasis on change in vernacular to aid in properly conceptualizing polyrhythms as a cohesive unit reflects a similar emphasis in the BC literature surrounding perception. This change has not been widely adopted.

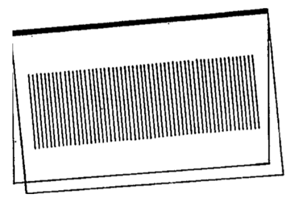
The evolution of practice and performance methods for polyrhythms has been spotty at best. Clayton (1972) suggests a practice method for learning polyrhythms on the drumset, advocating a three-step process: Find the common denominator, find the resultant rhythm, and perform the pattern in the hands later substituting the bass drum for the right hand. While the sequence provided may be helpful for *understanding* polyrhythms, switching the snare and bass drum after the initial learning of the polyrhythm is not aided by skill transfer, so the intermediate step of learning with the hands alone is unnecessary in order to achieve the final coordination pattern. Magadini (1973) suggests helpful strategies, advising performers to play the quicker rhythm with the hands and stomp the foot loudly with the slower rhythm and a metronome. Once again, the specific skill learned (which incorporates the foot and counting) would not transfer with limbs rearranged, though adjusting handedness and role in this way could aid in altering perception in a potentially helpful manner. Ashley (1984) suggests ways to develop coordination with the ultimate goal of improving drumset improvisation including slow practice, vocalization while playing, and switching hand roles. The BC literature supports the switching of hand roles to an extent, but it does not support slow practice (except for *understanding*) or vocalization explicitly.

Derrick (2000) troubleshoots common drumset coordination problems primarily by isolating limbs and combining them in different orders and arrangements with beginning, intermediate, and advanced examples. Separating limbs to aid in bimanual skill acquisition fundamentally disagrees with the BC literature. Also suggesting methods to improve drumset coordination, Ruttenberg (2002) advocates for the reorchestration of coordination exercises and claims that sound is an obstacle to learning. As discussed regarding FB, it is possible to become overly dependent on visual stimuli, but auditory FB is relatively immune to the guidance effect. In the pitched percussion domain, Venet (2017) advocates for the incorporation of polyrhythms into the keyboard warmup routine. Regular practice of polyrhythms would certainly aid in retention, and there is evidence to suggest that learning new BC patterns could be eased by regular exposure due to repeated implementation of the bimanual learning process. However, using the same polyrhythms for every warmup would likely not aid in the learning of new polyrhythms in the future.

Many of the practice methods proposed in the percussion literature are actually methods for *understanding* polyrhythms. Delp (1972) tackles this concept in an article that introduces steps for teaching polyrhythms that require the creation of a device using lines drawn on paper and a report cover (See Figure 1). It then suggests getting the rhythm to line up close to the visual guide and then “rounding off” to approximate the accurate polyrhythm (p. 41). While the concept of abstracting a rhythm to aid in cohesive perception is supported by the scientific literature, accuracy would surely suffer, and the use of augmented or concurrent auditory FB would be arbitrary. Kettle (1981) argues for the use of tuplets and rudiments as a basis for understanding polyrhythmic timing by grouping notes in various ways and adjusting footfalls (the point at which the foot taps or plays a pedal-activated instrument to indicate the felt pulse of a passage) to create the feeling of multiple simultaneous meters. The effect may be an unintentional reframing of the perceptual representation of the polyrhythm. Moore (1996) introduces a five-step sequence for learning polyrhythms: Determine the time signature,

Figure 1

Ron Delp's Report Cover Method



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determine the rhythmic skeleton, add accents to juxtapose meter, use a metronome to reflect the time signature, and perform the accents and metronome timing simultaneously. The jump to performing polyrhythms outright while the metronome clicks half of the rhythm disagrees with the BC literature on auditory FB. Similarly, Macdonald (2002) introduces a pedagogical sequence for teaching and learning polyrhythms: Get comfortable with tuplets and different accent patterns, figure out the polyrhythm by finding the lowest common denominator (drawing stems up and down to represent tuplets, vocalizing the subdivision, and applying meter using accents to separate meters), count each meter while playing the polyrhythm, alternate two halves of the polyrhythm against a metronome, and shift between various polyrhythms. The concept of *understanding* the polyrhythm prior to practice agrees with the scientific literature, but there is no basis to suggest that vocalizing or playing one half of the polyrhythm with auditory FB would be beneficial (unless that FB presented the entire perceptual polyrhythm). Shifting between polyrhythms before all are learned in their various permutations could also prove detrimental to the learning process if done too early, due to task-switching difficulties.

In an article meant to present a new way of conceptualizing motor patterns to ease the learning process for Brian Ferneyhough's *Bone Alphabet* for multiple percussion soloist, Karre (2012) advocates for the use of a "selection procedure" (p. 38), which accommodates one element of the music while sacrificing another element for later examination, creating a hierarchy of attention, and the creation of maps and diagrams to aid in the learning of complex coordination skills. The shifting of perception through attentional adjustments is supported in the scientific literature, and the idea that a visual aid with salient information could help with the learning of a complex coordination tasks is also supported. Some of the suggestions in this literature agree with the BC research incidentally, and many of them are time-consuming and potentially harmful to the learning process. Thanks to the emergence and popularity of fields such as cognitive science, other authors have tackled cognition directly through the lens of the practicing percussionist. In addition, some resources have been put forth that implement the ideas surrounding unified perception and salient visual FB found the in BC literature.

Perception, Feedback, and Cognition

An examination of the polyrhythmic percussion literature would not be complete without an inspection of the writings on perception, FB, and cognition. Perception is mostly addressed tangentially, but its presence in more recent percussion writings is an indicator that its importance is not lost on performers and educators. In an article meant to introduce an approach to learning polyrhythms that focuses on feeling and perception, Leake (2011) promotes yogic, meditative practice sessions, body kinesthetic[101] motions and vocables to develop multi-meter feel, awareness of "rhythmic culture shock" whereby multiple rhythms are felt simultaneously (p. 30), and utilizing changes in perception (analogizing cubist artwork). The idea that perception can influence polyrhythmic learning is supported by the BC literature, but body kinesthetics and vocalization are not supported and could potentially prove detrimental to the learning of a specific coordination pattern. Staebell (2015) attempts to develop a method for playing drumset that is "free" and "out of time" (p. 46). The author confuses polyrhythms for tuplets, but the juxtaposition of audience perception (out of time) and performer perception (strictly learned coordination pattern) mirrors the conversation surrounding internal and external perception in the BC literature. Suggesting ways to avoid injury in practice and performance for percussionists, Workman (2001) distinguishes between strength, coordination, and endurance, argues that resistance is an obstacle that challenges the ability to coordinate, advocates for energy conservation to increase endurance, and argues that performers should work with natural body movement to generally decrease resistance. The idea that resistance is an obstacle reflects the BC literature on force production, and there are links between "listening to the body" and the concept of internal and external perception (p. 53). Becoming more

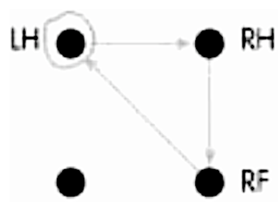
[101] For a definition of *kinesthetic*, see Appendix B.

attuned to the internal state during performance might very well promote an internal perception, highly advised by the BC literature.

FB is not addressed head-on, but one notational method deviates significantly from common notation standards. Abbott (1994) introduces a new way of conceptualizing four-limb coordination using a visual, graphic representation of coordination patterns on the drumset. Each limb is assigned one of four quadrants, and lines are used to signify direction of motion (See Figure 2). Cangelosi (2017) uses similar notation in a book designed to abstract BC movements into shapes, no doubt useful for promoting a unified perception. This reduction of visual noise to the most salient movement-oriented information agrees strongly with the BC research on visual FB and perception.

Figure 2

Louis Abbott's Directional Notation



Note. First appeared in *Percussive Notes.* Reprinted by permission of the Percussive Arts Society, Inc., 110 W. Washington Street, Suite A, Indianapolis, IN 46206; E-mail: percarts@pas.org; Web: www.pas.org. Reprinted from "The Square Concept," by L. Abbott, 1994, *Percussive Notes,* 32(5), 16.

In some percussion writing, cognition is discussed at length. Killingsworth (1995), for instance, applies cognitive science literature to multi-limb coordination procedures. The article includes an excellent overview of coordination and cognition with ample criticisms of trends in pedagogy during the time. The author advocates for a serial (instead of parallel) processing model whereby hands are learned together instead of separated, argues that interference between tasks increases when they are similar, and that brains only possess one processing mechanism for coordinated patterns in which only one stream of information can be processed at a time. The article criticizes standard music notation and audio FB that emphasizes a parallel processing model along with the incorrect usage of Jim Chapin's term "coordinated independence" (p. 72), and it distinguishes between the perception of the performer and the perception of the audience. Many of these themes are present in the scientific literature, but the current understanding of mechanisms in the brain—while incomplete—far surpasses the information available to Killingsworth at the time.

Little more than a decade later, Piper (2008) describes the cognitive processes behind coordination using the concept of "lines of communication" to address misfires in the brain (p. 58), suggesting that it is a lifelong problem. These misfires align well with the concept of neural crosstalk. The article describes motor messages as an "uncontrolled array of sparks and flashes that seem to be directed to anonymous limbs" (p. 58) and suggests three techniques for creating new coordination pathways; adding a limb on top of an ostinato in a separate limb, taking the music one beat at a time, or playing the part as written but manipulating time to focus only on perfect coordination. The latter method could be helpful for *understanding*, and the beat isolation method may aid in initial learning, but the ostinato method is potentially harmful to the BC learning process. In an article describing muscle memory from a cognitive point of view, Workman (2012) explains that neurological changes continue after practice has stopped, there are three stages for incorporating tasks into muscle memory (cognitive, associative, autonomic), increasing practice length can increase focus ability, and muscle memory happens in the brain (not the body). The article advocates the concept of correctly from the beginning to avoid incorrect muscle memory and argues that derailing muscle memory is caused by overthinking, which leads to performance anxiety. While it is easy to draw the conclusion that practice repetitions must approximate motor perfection from the outset in order to avoid the unintentional learning of mistakes, this disagrees with the BC literature on error due to frequency. Slow, correct playing does not always translate to fast, correct playing.

Lastly, Artimisi (2013) reveals the way in which motor skills are consolidated. The author defines consolidation as the extent to which a skill can be accurately recalled, distinguishes between explicit and implicit motor learning,[102] describes brain areas and their specialties regarding music, and relates skill development to learning a program in the brain. The article explains that the brain stores pattern sequences as whole instead of individual movements, describes "transfer" and "pattern storage"[103] (p. 50), advocates for "anchoring" to a metronome (pp. 50-51), and discusses the importance of practicing at a target tempo that approximates identical muscle movement. Furthermore, it explains that motor skills continue to improve up to four hours following a session followed by stagnation and discusses the critical role of sleep. This

[102] For definitions of *explicit motor learning* and *implicit motor learning*, see Appendix B.
[103] For a definition of *pattern storage*, see Appendix B.

may be the most agreeable article in *Percussive Notes*, *Rhythm! Scene,* or *Modern Drummer* with the BC literature to date.

Perception, FB, and cognition are addressed in a smaller, yet important, collection of percussion literature. Much of the literature provides anecdotal advice for the *understanding* of polyrhythms. While potentially beneficial in specific circumstances, generally applicable rules that avoid conflict with the BC research are difficult to come by. The rare article that addresses percussion performance and cognition fails to provide actionable suggestions that are specific to the learning of polyrhythms. Polyrhythms need a unique approach, and the percussion community may be overlooking the need for this endeavor. This need can be confronted by optimizing the learning process through the lens of BC research.

Chapter 6: Optimizing the Learning Process

Applying the BC literature, developing a new learning sequence, and implementing new FB tools will cultivate a new landscape for polyrhythmic practice. This novel learning process needs to be formed due to the unique way in which polyrhythms are engaged by the nervous system, and formulation of this optimal learning environment cannot begin without an application of the BC research to percussion pedagogy.

Applying the Bimanual Coordination Research

Much of the BC literature is immediately applicable to performance and practice. However, some of the research implications cannot be realized without the creation of new tools. Applying BC findings to the percussion practice routine is much like imposing a new philosophy on the practitioner. The implementation of this philosophy will give rise to a new pedagogical model, but merely internalizing the core concepts is enough for immediate benefit to take place in the practice room and on stage. In order to optimize the learning process for polyrhythms, the BC research on the nervous system, perception, FB, and error must be extensively applied to the percussion performance environment.

The nervous system literature provides abundant insight into BC, and this insight proves invaluable for polyrhythmic performance. Since skill does not transfer when novel horizontal components are introduced to the required movement, polyrhythms must be learned separately in each context. Direction of motion cannot be imposed upon a previously learned polyrhythm without equal effort. The slow hand needs to be interleaved into the timing of the fast hand, but this will occur naturally. The second note of any musical phrase determines the tempo of the passage, and the second note is played by the fast hand in all polyrhythms. Task-switching derails the learning process, so transitions between movements must be addressed as an integral component of the skill. Polyrhythmic *understanding* is distinct from motor skill acquisition, and the process of physically learning a new polyrhythm does not truly begin until it is played in its exact motor sequence. Moreover, age differences in BC ability and a lack of skill transfer suggest that as much polyrhythmic learning as possible should be undertaken in young adulthood. IHI and neural crosstalk literature lead to realizations in hand relationships. A static hand will tend to activate along with a moving hand, a slow hand will tend to speed up to match a fast hand, and a quiet hand will tend to increase in volume to imitate a loud hand. These adjustments are involuntary, but attention can be placed on the hand most likely to engage in coupling to seek out these errors and make adjustments in real time. Finally, it is essential that polyrhythms are learned with both limbs simultaneously. Not only is learning the individual rhythms unhelpful, it also promotes a deleterious dual perception of the coordination pattern.

Beyond a mechanical look at the nervous system, perceptual studies highlight the importance of navigating interlimb relationships and the internalization of polyrhythms. A hand is more likely to make mistakes if it is more static, slower, or quieter. Performers may often think of a static hand as more stable, but attentional demands flip this idea on its head in the face of polyrhythmic coordination. The busier hand tends to be more accurate. The natural consequence is a direction of attention to the mistake-prone limb, and this attentional adjustment can cause increases of height in that limb. While error tends to increase when the nondominant hand is fastest, speed has a greater effect than handedness anyway, so it is likely that this tendency will become a non-issue with experience. Regardless, any effect of the dominant hand on the nondominant hand can be mitigated by directing focus to the nondominant hand. When using hand speed to determine attentional priorities, the fast hand is the best anchor point for accuracy. An ideal approach would periodically involve paying attention to the slow hand for error correction and focusing primarily on the fast hand for general stability.

All of these suggestions assume an externally guided process, but reliance on external stimuli (such as stick height or playing area) should be minimized. The end goal is an absolute internalization of the polyrhythm. Lastly, because of the differences in perception at various tempos, practicing slow does not aid in fast playing whatsoever, and thinking about fine details at fast speeds can derail performance.

FB in the BC research typically refers to real time visual or auditory stimulus that provides salient information about performance. While this form of FB is challenging to implement in an everyday practice session, the lessons gleaned from these studies can still be applied to familiar tools. Visual FB should be used primarily to aid in *understanding* polyrhythms.

During the early learning stages, visual information can help to formulate a unified perception of complex movement patterns. Though dynamics can be learned with the aid of a visual tool, the tool needs to be simple and carefully implemented. Because of this restriction, it may be best to avoid using visual FB in this manner altogether. Similarly, augmented visual FB can have a robust effect on speed of learning, but it may only aid performance while present, and playing can worsen once the FB is removed. One of the side-effects of visual FB is an over-adjustment to error. These over-adjustments can potentially help by causing closer approximations to correct playing over time. No matter the usage, visual FB must accurately represent the task at hand. Auditory FB, on the other hand, may be more beneficial to learning because of improvements in consolidation and internalization. The most striking difference between the two forms of FB is that auditory benefits remain when the FB is removed. These benefits are most powerful when sonification occurs in conjunction with movement. No matter the FB used, its use should be diminished according to a fading schedule[104] to promote internalization and prepare for live performance.

Even with all these tools at the performer's disposal, error is inevitable. The way in which error occurs during BC is distinct from other forms of motor coordination, and this distinction is largely due to playing frequency. Of primary consideration is the selection of an appropriate practice tempo. Since practicing at slower speeds has virtually no bearing on faster performance, practicing close to the desired tempo at the outset is preferable. It is of course necessary to achieve a solid understanding of the polyrhythm first. One tool to aid in this endeavor involves anchoring timing to wrist flexion and pronation checkpoints—moments in which the implement strikes a playing surface or moves inward toward the body. While polyrhythms are difficult to master regardless of performance experience, untrained percussionists may benefit to a greater extent from video FB. Additionally, inexperienced players should grow accustomed to resisting collapses from antiphase to inphase motion. Even if the performer produces errors, the act of resistance is a skill that must be nurtured. In this way, the beginning steps for polyrhythmic training involve familiarization with a likely unprecedented system of learning. As experience with the system increases, new polyrhythms (and old polyrhythms in new contexts) will be learned with greater ease. Despite this, the process will start from the beginning each time, and relatively little transfer will occur from one polyrhythm to the next. With a wealth of BC insight to employ, a new pedagogical sequence for polyrhythms can be realized.

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[104] For a definition of *fading schedule*, see Appendix B.

Developing a Pedagogical Sequence

The suggestions for this new pedagogical sequence would be best implemented with supplemental materials that, to the author's knowledge, do not exist in any comprehensive format at the time of this writing. Until such a resource exists, much of the work rests on the shoulders of the teacher or performer to notate, record, and otherwise create and implement the tools outlined in this section. This sequence might be utilized as a curricular unit on polyrhythmic coordination during undergraduate studies, but aspects would also function well in targeted sessions for specific musical passages. The themes from the BC literature inform this approach, and while the sheer number of steps and variations may seem overwhelming, the peculiar nature of polyrhythmic skill acquisition necessitates this procedure. At minimum, this sequence will make clear the importance of beginning complex coordination patterns early in the performance career. Lastly, the sequence does not include a prescriptive method for notating composite rhythms—ample resources exist in this area, and some are discussed in the previous chapter. A methodical system for addressing polyrhythms will require variations in force, directionality, and combination exercises to promote adaptability. The development of this system is the final step to optimizing the learning process for polyrhythms.

To begin, the polyrhythm should be learned with both limbs simultaneously on a single playing surface. The tempo must be at a speed that allows for easy recognition of the composite rhythm. Ideally, the dual rhythmic nature of the polyrhythm should be hidden from the performer and revealed only after the coordination is comfortable (possibly many practice sessions in the future). After initial skill acquisition, ease at various tempos should be attained, but for perceptual reasons, the priority should be skill acquisition at moderate and fast tempos.[105] At this point the polyrhythm is learned, but it must be relearned in various contexts in order to promote adaptability.

Variations in force include all dynamic adjustments related to expression and articulation. The polyrhythm should be played with all various combinations of dynamics: *loud-loud*, *loud-medium*, *loud-soft*, *medium-loud*, *medium-medium*, *medium-soft*, *soft-loud*, *soft-medium*, *soft-soft* (See Table 1). While this is by no means a comprehensive matrix of dynamic combinations, it is sufficient to allow for approximation in context as needed. These dynamic variations assume constant playing at the suggested volumes, but sudden force adjustments

[105] Polyrhythms should be learned accurately at moderate tempos prior to ultimately crossing a tempo threshold informed by perceptual constraints. For a table of recommended minimum fast tempos, see Appendix C.

Table 1

Dynamic Variation Matrix for the 3:2 Polyrhythm

#	3	2
1	*Loud*	*Medium*
2	*Loud*	*Soft*
3	*Medium*	*Loud*
4	*Medium*	*Soft*
5	*Soft*	*Loud*
6	*Soft*	*Medium*

Note. Shaded boxes are used to distinguish between adjustments in the fast hand. Each row contains the exercises number, the fast hand pattern (3), and the slow hand pattern (2).

should also be addressed. To do this, the polyrhythm should be played with all various combinations of accent patterns. In a 3:2 polyrhythm, this includes accenting the *first*, *second*, *third*, *first-second*, *second-third*, and *first-third* partials of the fast hand as well as the *first* and *second* partials of the slow hand (See Table 2). Once all these combinations are comfortable, they need to be learned against one another. To achieve this, the performer should systematically cycle through each accent pattern in one hand and then repeat the cycle after adjusting the accent pattern of the other hand.

Directional variations introduce horizontal adjustments to the polyrhythm. These adjustments can be distilled into two directions: *toward* the body (in) and *away* from the body (out). A more complete practice regimen might include left, right, forward, and back motions (not to mention oblique patterns), but internalization of the polyrhythm utilizing an in-out

Table 2

Force Variation Matrix for the 3:2 Polyrhythm

#	3	2	#	3	2
7	*o o o*	*> o*	*17*	*o o >*	*o >*
8	*o o o*	*o >*	*18*	*> > o*	*o o*
9	*> o o*	*o o*	*19*	*> > o*	*> o*

Table 2 Continued

Force Variation Matrix for the 3:2 Polyrhythm

#	3	2	#	3	2
10	*> o o*	*> o*	*20*	*> > o*	*o >*
11	*> o o*	*o >*	*21*	*o > >*	*o o*
12	*o > o*	*o o*	*22*	*o > >*	*> o*
13	*o > o*	*> o*	*23*	*o > >*	*o >*
14	*o > o*	*o >*	*24*	*> o >*	*o o*
15	*o o >*	*o o*	*25*	*> o >*	*> o*
16	*o o >*	*> o*	*26*	*> o >*	*o >*

Note. Shaded boxes are used to distinguish between adjustments in the fast hand. Each row contains the exercises number, the fast hand pattern (3), and the slow hand pattern (2). The “o” symbol indicates an absence of articulation, and the “>” symbol indicates louder volume or greater implement heights.

framework allows for maximal adaptability to various performance contexts. As with force variations, polyrhythms should be played with all various combinations of directionality. Stationary (still) moments must be included as well. In a 3:2 polyrhythm, this includes *out-still*, *still-out, in-still, still-in, out-in*, and *in-out* for the fast hand and *still, out*, and *in* for the slow hand. In the same fashion as the force variations, the performer should cycle through each directionality variation against the other. (See Table 3).

The last stage of the process should include all combinations of force variations and directional variations. All dynamic patterns should be played in tandem with all direction patterns, then the dynamic patterns should be replaced with the accent patterns. Once this practice regimen is complete and comfortable, the percussionist should be able to confidently prepare any polyrhythm for use in most contexts. However, any attempt to play a 2:3 polyrhythm (hands reversed) will not benefit from the work done on the 3:2 polyrhythm. Therefore, the entire practice sequence must be undertaken for all common polyrhythms in all common limb

Table 3

Direction Variation Matrix for the 3:2 Polyrhythm

#	3	2	#	3	2
27	↑ o	o	36	o ↓	o
28	↑ o	↑	37	o ↓	↑
29	↑ o	↓	38	o ↓	↓
30	o ↑	o	39	↑ ↓	o
31	o ↑	↑	40	↑ ↓	↑
32	o ↑	↓	41	↑ ↓	↓
33	↓ o	o	42	↓ ↑	o
34	↓ o	↑	43	↓ ↑	↑
35	↓ o	↓	44	↓ ↑	↓

Note. Shaded boxes are used to distinguish between adjustments in the fast hand. The "o" symbol indicates an absence of horizontal motion, the "↑" symbol indicates motion out away from the body, and the "↓" symbol indicates motion in toward the body.

configurations. Fortunately, directional variations do not need to be applied to the feet. With careful use of FB tools, the challenge of this rigorous process can be diminished.

Visual and Auditory Aids

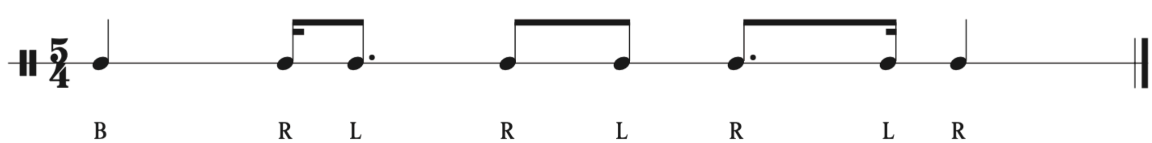
The outlined sequence may seem insurmountable, but its difficulty is significantly diminished with the creative use of visual and auditory aids. The BC literature leaves little room for improvisation, but free tools already exist that can aid in notation and sound-creation for those hoping to learn as fast as possible with maximum retention. Future research should include the creation and collection of resources mentioned in this section, and careful attention should be placed on perception of the polyrhythms as cohesive units. In order to utilize FB properly, timing, notational strategies, and sonification methods must be addressed. An optimal learning process for polyrhythms is incomplete without the inclusion of visual and auditory aids.

Both forms of FB should be used to help with the learning of polyrhythms. Visual FB should be used initially and then removed gradually. Once correct repetitions begin to occur, the visual FB should be removed altogether unless needed for reference between repetitions.[106] Auditory FB should be used from the outset, and while it less likely for the performer to become dependent on auditory FB, it should still be removed with a fading schedule. The performer should utilize the visual FB primarily during the *understanding* phase and the auditory FB during the motor skill acquisition phase. Once the polyrhythm has been learned sufficiently, the auditory FB can be revisited to aid in memory recall for future practice sessions.

The most basic visual tool is sheet music. Each step of the sequence should be clearly and simply notated, reflecting the most salient information to promote internalization. Additionally, it should not be clear to the inexperienced learner which polyrhythm is notated. To achieve this, the composite rhythm should be notated with simple, familiar note values and meters, and sticking should be provided to ensure proper coordination. For instance, a 5:4 polyrhythm might be written as one quarter-note (both), one sixteenth-note (right), one dotted eighth-note (left), two eighth-notes (right, left), one dotted eighth-note (right), one sixteenth-note (left), and one quarter-note (right), all notated on a single line of the staff (See Figure 3).

Figure 3

Composite Notation of a 4:5 Polyrhythm



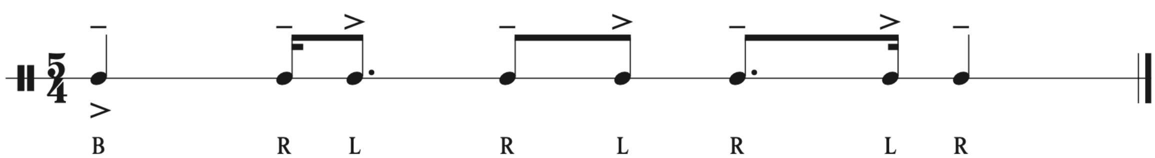
These rhythms are common in middle school percussion literature, and it is likely that the coordination will be executed quickly. This notation should be utilized for the first step of the sequence. For the dynamic variations, articulation markings should be used for ease of reading. In non-pitched percussion music, tenuto markings are often used to denote light accents, and in this scenario, tenuto markings can indicate medium volume or implement height. Accents, of course, indicate high volume, and no articulation indicates low volume. Since the first note is played with both hands, an articulation marking should be placed on the top and bottom of the staff (each indicating a separate hand). Applying this concept to the previous 5:4 polyrhythm example, the order of articulations in a medium-loud dynamic variation is as follows: *tenuto*

[106] For an example of a transitional visual representation to aid in the eventual removal of visual FB, see Appendix D.

(top) and *accent* (bottom), *tenuto, accent, tenuto, accent, tenuto, accent*, and *tenuto* (See Figure 4). It is critical that notation during this step is based on the composite rhythm.

Figure 4

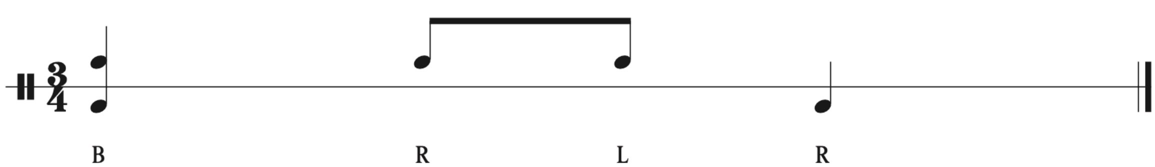
Force Notation of a 4:5 Polyrhythm



While notating the actual polyrhythm with a single dynamic marking for each tuplet is easier to accomplish, such a depiction is detrimental to learning. This same articulation approach can be applied for the accent pattern variations, and this concludes force combinations. At this point in the sequence, different lines or spaces on the staff can be used to indicate direction of motion. Movement from a note lower on the staff to a note higher on the staff represents motion outward away from the body, and movement from a note higher on the staff to a note lower on the staff represents motion inward toward the body (See Figure 5). This notation is adaptable for various contexts, such as keyboard, timpani, multiple percussion, and drumset practice. Once again, visual FB must be removed as soon as the coordination pattern is successfully achieved to avoid dependence on the sheet music.

Figure 5

Directional Notation of a 2:3 Polyrhythm



Note. See exercise 37 in Table 3.

Metronomes are possibly the most common auditory FB tool, and proper use can help facilitate the learning of polyrhythms. The metronome should have the ability to play multiple tuplets simultaneously and vary the volume of each tuplet for the dynamic variations. If a metronome is used, it is imperative that the sound created by each tuplet is identical. Even with this precaution, the very nature of setting up a metronome exposes the duality of the polyrhythm, so this should not be done until the basic coordination pattern has already been learned. To facilitate this, an audio clip of the polyrhythm as a composite rhythm should be utilized during initial practice. The ideal scenario would involve practicing along with an audio clip that matches the specific stage of the practice sequence exactly. While a resource like this does not yet exist, music notation software can be used to serve this purpose. The additional benefit of notational software is that it allows for melodic sonification. As long as the melodic content supports the composite rhythm instead of the distinct tuplets, it will support learning and retention.

Conclusion

The learning of polyrhythms is facilitated by the brain in novel ways dependent upon several contextual variables, and the uniqueness of this learning process requires a rethinking of the current pedagogical approach. Literature on the nervous system includes an exploration of brain structure, neural crosstalk, and IHI. These studies expose the importance of learning polyrhythms with all necessary limbs simultaneously. Research on perception during bimanual skill learning addresses issues of coupling, handedness, role, and internal perception. These studies highlight the importance of using the fast hand as an anchor for timing accuracy and developing an internalized representation of the polyrhythm over time. Stepping away from internal perception and toward external stimuli, research in the area of FB inspect visual and auditory sensation. This inspection reveals a significant benefit of auditory FB for internalization, though visual FB can be immensely useful during early learning stages if it is removed quickly. Studies concerned with error examine frequency, collapse, symmetry, physiology, and training. This research points to the brain's treatment of fast and slow playing as disparate actions and accentuates the potential benefits of anchoring timing to motions in toward the body. The percussion literature lacks a comprehensive approach to polyrhythmic practice, performance, and pedagogy, though an enormous number of resources exist to aid in *understanding* the rhythmic relationships inherent in polyrhythmic coordination.

The learning process for polyrhythms benefits from this new system because of the unique way in which this style of coordination interfaces with the brain and body. However, polyrhythms may appear in such a way that practicing them out of context is not useful. In Iannis Xenakis' *Rebonds,* for instance, a nested three-tuplet is sandwiched into the third partial of a six-tuplet in one hand while the other hand performs a five-tuplet. In Michael Gordon's *XY*, a 6:5 polyrhythm is performed in which the six-tuplet is grouped in two and the five-tuplet is grouped in four (mostly). *Canaries* by Elliot Carter has an infamous passage in which one hand engages in gradual performance of faster metric modulations against a constant rhythmic pulse in the other hand. Musical situations like these require the implementation of a system informed by the rules outlined in this chapter, but creative adjustments must be made as appropriate. No one system can prepare an individual for any of these three examples. However, familiarity with the peculiar nature of polyrhythmic learning can predispose performers to conquering the challenges faced in this musical literature.

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Part Two

Program Notes

DMA Percussion Solo Recital

UNIVERSITY OF KENTUCKY
SCHOOL OF MUSIC
PRESENTS

Christian Swafford

In a Graduate Percussion Recital

March 21, 2022

Singletary Center for the Arts

5:00 pm

*Note: Latecomers will be seated at intermission

Program

Psalm 3 (2009)	Sarah Hennies (b. 1979)
Obbligato Snare Drum Music No. 1: "The Power of Love" (2020)	Thomas Kotcheff (b. 1988)
Box Truck Blues: Ambulations from Athens to Knoxville (2020)	Peter Naughton (b. 1991)

World Premiere

Echolalia (2006)	Mark Applebaum (b. 1967)
XY (1997)	Michael Gordon (b. 1956)

For recording purposes, please hold applause until after each set/piece and have cell phones on silent. As a courtesy to performers and other audience members, please turn off and put away all electronic devices. The use of recording and photographic equipment is permitted only by approved University personnel. No food or drink is permitted in this performance venue. We ask that you remain seated throughout the performance and, if you must exit, that you wait until applause.

This recital is presented in partial fulfillment of the requirements of the Doctor of Music in Performance. Christian Swafford is a student of Professor James Campbell.

Program Notes

Psalm 3 — Sarah Hennies

Inspired by Alvin Lucier's solo for triangle, "Silver Streetcar for the Orchestra" and Hennies' early vibraphone piece, "untitled (1918-2000)", "Psalm 3" is one of three "Psalms" written to expose the highly anomalous acoustic characteristics of conventional percussion instruments. When heard live, the piece creates a three-dimensional listening experience that produces bizarre tones, echoes, and resonances. Composed for solo woodblock, "Psalm 3" amplifies the complex relationship between sound, performer, and space.

Sarah Hennies, born in Louisville, KY, is a composer based in Ithaca, NY whose work is concerned with a variety of musical, sociopolitical, and psychological issues including queer and trans identity, psychoacoustics, and the social and neurological conditions underlying creative thought. Sarah is currently a Visiting Assistant Professor of Music at Bard College.

Obbligato Snare Drum Music No. 1: "The Power of Love" — Thomas Kotcheff

Written for Michael Compitello, the piece is a marriage of Kotcheff's love of snare drum and Celine Dion. It utilizes variable snare drum striking areas and the inclusion of metal sonorities to enhance the effect of distortion in the digital audio component. The difficult technical challenge presented to the performer is contrasted almost sarcastically by Celine's beautiful singing.

Thomas Kotcheff is a Los Angeles based composer and pianist. His music has been described as "truly beautiful and inspired" and "explosive". Thomas currently serves on the music theory and ear training faculty at the Colburn School and is a faculty member of the Los Angeles Philharmonic's Composer Fellowship Program.

Box Truck Blues: Ambulations from Athens to Knoxville — Peter Naughton

Written for Christian Swafford, Box Truck Blues is a reflection on time spent in Knoxville, TN. Late one night, Peter got lost in the mountains on the way back to Knoxville, surrounded by darkness and the wrath of Mother Nature, ill-equipped to navigate home in an old, worn-down box truck. This journey influenced the composition of the piece, and the performance is informed a great deal by Christian's memories of home.

Peter Naughton is a versatile performer residing in Iowa City, specializing in jazz keyboard improvisation, contemporary chamber music, and steel pan. His music blends the aesthetics of contemporary classical works with the melodic and harmonic sensibilities of commercial music, finding inspiration from Bill Frisell, Pat Metheny, David Lang, The Caribbean Jazz Project, and Alejandro Viñao. In May 2020, he released his first studio album, Southern Gothic. Peter holds degrees from The University of Iowa and The University of Tennessee, Knoxville. He is currently adjunct professor of percussion at Monmouth College and a longtime percussion faculty member for Birch Creek Music Performance Center.

Echolalia — Mark Applebaum

Derived from Applebaum's piece "Asylum", "Echolalia" is a theatric manifestation of shared psychosis and dissociative identity disorder. The performer attempts a musical expression but suffers an apraxia that manifests itself in a completely different medium, as a series of 22 Dadaist rituals performed in rapid succession.

Mark Applebaum, Ph.D. is the Edith & Leland Smith Professor of Composition at Stanford University. Many of his pieces are characterized by challenges to the conventional boundaries of musical ontology. Applebaum is also a jazz pianist and builds electroacoustic sound-sculptures out of junk, hardware, and found objects. At Sanford, Applebaum is the founding director of the Stanford Improvisation Collective. He serves on the board of Other Minds and as a trustee of Carleton College.

XY — Michael Gordon

A solo for five tuned drums, "XY" is a massive exercise in independence and coordination. Throughout the piece, the right and left hand of the performer get louder and softer in reverse symmetry, eventually changing speeds independently as well. The rate of change is explored in addition to the stacking of perceived rhythms or pulses. Gordon speaks of the hands as if they were independent beings, and indeed they practically are. When he was imagining the music of "XY", he thought of a double helix of DNA, which wraps around itself and spirals upwards.

Michael Gordon's music merges subtle rhythmic invention with incredible power embodying, in the words of *The New Yorker's* Alex Ross, "the fury of punk rock, the nervous brilliance of free jazz and the intransigence of classical modernism." Over the course of his composing career, Gordon has produced a strikingly diverse body of work, ranging from large-scale pieces for high-energy ensembles to major orchestral commissions to works conceived specifically for the recording studio. Transcending categorization, this music represents the collision of mysterious introspection and brutal directness.

UNIVERSITY OF KENTUCKY

SCHOOL OF MUSIC

PRESENTS

Timber

A Graduate Chamber Recital

April 22, 2022

The Arboretum, State Botanical Garden of Kentucky

1:00 pm

Program

Timber (2011) Michael Gordon
(b. 1956)

About *Timber*:

Timber is a piece written for six amplified simantra — or wooden planks. The complex timbral characteristics of the wood are amplified electronically creating an ethereal sonic experience and encouraging a meditation in sound, rhythm, and nature. Bewilderingly challenging, yet soothing and contemplative, the piece sounds as if the forest is whispering just above the rhythmic swells of the performers.

About Michael Gordon:

Michael Gordon is known for his monumental and immersive works. *Decasia*, for 55 retuned spatially positioned instruments (with Bill Morrison's accompanying cult-classic film) has been featured on the Los Angeles Philharmonic's Minimalist Jukebox Festival and at the Southbank Centre. *Timber*, a tour-de-force for percussion sextet played on amplified microtonal simantras has been performed on every continent, including by Slagwerk Den Haag at the Musikgebouw and Mantra Percussion at BAM. *Natural History*, a collaboration with the Steiger Butte Drum of the Klamath tribe, was premiered by the Britt Festival Orchestra and Chorus on the rim of Crater Lake (Oregon) by conductor Teddy Abrams and is the subject of the PBS documentary *Symphony for Nature*. Gordon's vocal works include *Anonymous Man*, an autobiographical choral work for The Crossing; the opera *What to wear* with the legendary director Richard Foreman; and the film-opera *Acquanetta* with director Daniel Fish. Recent recordings include *Clouded Yellow*, Gordon's complete string quartets performed by the Kronos Quartet.

This recital is presented in partial fulfillment of the requirements of the doctoral studies of Christian Swafford. Christian is a student of Professor James Campbell.

UNIVERSITY OF KENTUCKY

SCHOOL OF MUSIC

PRESENTS

Polyrhythmic Pathways

A Graduate Lecture Recital

April 10, 2023

Carl Lampert Room 22, College of Fine Arts

5:30 pm

Program

This lecture recital features excerpts from the following repertoire.

Khan Variations (2001)	Alejandro Viñao (b. 1951)
Rebonds (1989)	Iannis Xenakis (1922-2001)
Canaries (1968)	Elliot Carter (1908-2012)
XY (1997)	Michael Gordon (b. 1956)

For recording purposes, please hold applause until after each set/piece and have cell phones on silent. As a courtesy to performers and other audience members, please turn off and put away all electronic devices. The use of recording and photographic equipment is permitted only by approved University personnel. No food or drink is permitted in this performance venue. We ask that you remain seated throughout the performance and, if you must exit, that you wait until applause.

This recital is presented in partial fulfillment of the requirements of the Doctor of Musical Arts in Performance. Christian Swafford is a student of Professor James Campbell.

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Gordon, M. (2011). *Timber* [Percussion score]. Red Poppy Music.

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Appendices

Appendix A

List of Abbreviations

Abbreviation	Term
BC	bimanual coordination
CC	corpus callosum
DAW	digital audio workstation
DTI	diffusion tensor imaging
FA	fractional ansiotropy
FB	feedback
LCM	least common multiple
IHI	interhemispheric inhibition
iSP	ipsilateral silent period
TBI	traumatic brain injury
TMS	transcranial magnetic stimulation

Appendix B

Glossary

Term	Definition
acallosal	lacking a corpus callosum (Merriam-Webster)
amplitude	the extent or range of a quality, property, process, or phenomenon: such as the extent of a vibratory movement (as of a pendulum) measured from the mean position to an extreme (Merriam-Webster)
anchoring	to act or serve as an anchor for (Merriam-Webster)
anisotropic	when the diffusion of water molecules in diffusion tensor imaging encounters resistance, indicating directionality to the fibers (Wahl et al., 2016)
anterior	(1) relating to or situated near or toward the head or toward the part in headless animals most nearly corresponding to the head (2) situated toward the front of the body (Merriam-Webster's Medical Dictionary, 2016)

Appendix B Continued

Term	Definition
augmented feedback	feedback from an external source that can be provided as knowledge of result or knowledge of performance (Wälchle et al., 2016)
assimilation	the process of receiving new facts or of responding to new situations in conformity with what is already available to consciousness (Merriam-Webster's Medical Dictionary, 2016)
asymmetry	lack or absence of symmetry as lack of coordination of two parts acting in connection with one another (Merriam-Webster's Medical Dictionary, 2016)
axon	a usually long and single nerve-cell process that usually conducts impulses away from the cell body (Merriam-Webster)
bilateral	of, relating to, or affecting the right and left sides of the body or the right and left members of paired organs (Merriam-Webster's Medical Dictionary, 2016)
bimanual	done with or requiring the use of both hands (Merriam-Webster's Medical Dictionary, 2016)
callosal	of, relating to, or adjoining the corpus callosum. (Merriam-Webster's Medical Dictionary, 2016; Wahl et al., 2016)
callosotomy	the surgical elimination of a portion of the corpus callosum (American Psychological Association)
cerebellum	a large dorsally projecting part of the brain concerned especially with the coordination of muscles and the maintenance of bodily equilibrium, situated between the brain stem and the back of the cerebrum, and formed in humans of two lateral lobes and a median lobe (Merriam-Webster's Medical Dictionary, 2016)
cognitive	of, relating to, or being conscious intellectual activity (as thinking, reasoning, remembering, imagining, or learning words) (Merriam-Webster's Medical Dictionary, 2016)
common coding theory	posits (1) perceiving an action activates the same representations of motor plans that are activated by performing that action (2) because of individual differences in the way actions are performed, observing recordings of one's own previous behavior activates motor plans to an even greater degree than observing someone else's behavior (Tye-Murray et al., 2013)
consolidation	the extent to which a skill can be correctly recalled (Artimisi, 2013)

Appendix B Continued

Term	Definition
constrained action hypothesis	states that focusing attention on action outcomes rather than body movement improves motor performance (Allingham & Wöllner, 2021; Shea et al., 2016)
constraint	a constraining condition, agency, or force (Merriam-Webster)
contextual interference	the interference that results from performing various tasks or skills within the context of practice (Pauwels et al., 2014)
contralateral	occurring on, affecting, or acting in conjunction with a part on the opposite side of the body (Merriam-Webster's Medical Dictionary, 2016)
coordination	(1) the act or action of bringing into a common action, movement, or condition (2) the harmonious functioning of parts (as muscle and nerves) for most effective results (Merriam-Webster's Medical Dictionary, 2016)
corpus callosum	the great band of commissural fibers uniting the cerebral hemispheres (Merriam-Webster's Medical Dictionary, 2016)
cortical	(1) of, relating to, or consisting of cortex (2) involving or resulting from the action or condition of the cerebral cortex (Merriam-Webster's Medical Dictionary, 2016)
cortico-	(1) cortex (2) cortical and (Merriam-Webster's Medical Dictionary, 2016)
corticospinal	of or relating to the cerebral cortex and spinal cord or to the corticospinal tract (Merriam-Webster's Medical Dictionary, 2016)
corticospinal tract	any of four columns of motor fibers of which two run on each side of the spinal cord and which are continuations of the pyramids of the medulla oblongata (Merriam-Webster)
coupling	the act of bringing or coming together (Merriam-Webster)
diffusion tensor imaging	the diffusion of water molecules into brain fibers for imaging purposes (Wahl et al., 2016)
demyelinating	causing or characterized by the loss or destruction of myelin (Merriam-Webster's Medical Dictionary, 2016)
dendrites	any of the usually branching protoplasmic processes that conduct impulses toward the body of a neuron (Merriam-Webster)
excitatory	tending to induce excitation (as of a neuron) (Merriam-Webster's Medical Dictionary, 2016)

Appendix B Continued

Term	Definition
explicit motor learning	learning generated by verbal knowledge of movement performance involving cognitive stages within the learning process and dependent on working memory involvement (Jie et al., 2018)
extension	(2) an unbending movement around a joint in a limb (as the knee or elbow) that increases the angle between the bones of the limb at the joint (Merriam-Webster's Medical Dictionary, 2016)
fading schedule	the process of decreasing the amount of feedback provided as practice progresses (Dyer et al., 2017a; Hodges et al., 2003; Shea et al., 2016)
feedback	the return to a point of origin of evaluative or corrective information about an action or process (Merriam-Webster's Medical Dictionary, 2016)
flexion	(1) a bending movement around a joint in a limb (as the knee or elbow) that decreases the angle between the bones of the limb at the joint (2) a forward raising of the arm or leg by a movement at the shoulder or hip joint (Merriam-Webster's Medical Dictionary, 2016)
fractional anisotropy	a value used in diffusion tensor imaging to determine whether brain fibers are isotropic or anisotropic (Wahl et al., 2016)
functional magnetic resonance imaging	magnetic resonance imaging used to detect physical changes (as of blood flow) in the brain resulting from increased neuronal activity (as during performance of a specific cognitive task) (Merriam-Webster's Medical Dictionary, 2016)
gamma-aminobutyric acid	an amino acid C4H9NO2 that is a neurotransmitter that induces inhibition of postsynaptic neurons (Merriam-Webster's Medical Dictionary, 2016)
glutamate	a salt or ester of glutamic acid; especially one that functions as an excitatory neurotransmitter (Merriam-Webster's Medical Dictionary, 2016)
glutamatergic	liberating, activated by, or involving glutamate (Merriam-Webster's Medical Dictionary, 2016)
guidance hypothesis	posits that knowledge of results enhances performance when it is present but degrades learning if it is given too frequently (Salmoni et al., 1984; Shea et al., 2016)
gyrus	a convoluted ridge between anatomical grooves (Merriam-Webster)
handedness	a tendency to use one hand rather than the other (Merriam-Webster's Medical Dictionary, 2016)

Appendix B Continued

Term	Definition
haptic	(1) relating to or based on the sense of touch (2) characterized by a predilection for the sense of touch (Merriam-Webster's Medical Dictionary, 2016)
homologous	having the same relative position, value, or structure (Merriam-Webster's Medical Dictionary, 2016)
inhibition	the act or an instance of inhibiting or the state of being inhibited (1) as a restraining of the function of a bodily organ or an agent (as an enzyme) (2) interference with or retardation or prevention of a process or activity (Merriam-Webster's Medical Dictionary, 2016)
interhemispheric	extending or occurring between hemispheres (as of the cerebrum) (Merriam-Webster's Medical Dictionary, 2016)
interhemispheric inhibition	the inhibition of signaling in the brain across hemispheres
implicit motor learning	learning that progresses with no or minimal increase in the verbal knowledge of movement performance and without awareness (Jie et al., 2018)
inter-	between, among (Merriam-Webster's Medical Dictionary, 2016)
interlimb	between or among the limbs
interneurons	a neuron that conveys impulses from one neuron to another — called also associative neuron, internuncial, internuncial neuron (Merriam-Webster's Medical Dictionary, 2016)
intra-	(a) within, (b) during, (c) between layers of (Merriam-Webster's Medical Dictionary, 2016)
intralimb	within the limbs
intrasulcal	within the sulcus
intrasulcal length of the precentral gyrus	within the sulcal length of the gyrus containing the motor area immediately anterior to the central sulcas (Merriam-Webster)
ipsilateral	situated or appearing on or affecting the same side of the body (Merriam-Webster's Medical Dictionary, 2016)

Appendix B Continued

Term	Definition
ipsilateral silent period	a frequently measured index of interhemispheric inhibition (Kuo et al., 2017)
isometric	of, relating to, involving, or being muscular contraction (as in isometrics) against resistance, without significant change of length of muscle fibers, and with marked increase in muscle tone (Merriam-Webster's Medical Dictionary, 2016)
isotropic	when the diffusion of water molecules in diffusion tensor imaging encounters little to no resistance in any direction, indicating a lack of directionality to the fibers (Wahl et al., 2016)
kinesthetic	a sense mediated by end organs located in muscles, tendons, and joints stimulated by bodily movements and tensions; also, sensory experience derived from this sense (Merriam-Webster's Medical Dictionary, 2016)
localization	(1) to make local or orient locally (2) to assign to or keep within a definite locality (Merriam-Webster)
locus	(1) a place or site of an event, activity, or thing (Merriam-Webster's Medical Dictionary, 2016)
microstructure	microscopic structure (Merriam-Webster's Medical Dictionary, 2016)
mirror movements	involuntary activity of the homologous contralateral limb that is associated with voluntary unilateral actions (Kennedy et al., 2016)
monitor	to watch, observe, or check closely or continuously (Merriam-Webster's Medical Dictionary, 2016)
motor area	any of various areas of cerebral cortex believed to be associated with the initiation, coordination, and transmission of motor impulses to lower centers; specifically, a region immediately anterior to the central sulcus having an unusually thick zone of cortical gray matter and communicating with lower centers chiefly through the corticospinal tracts (Merriam-Webster's Medical Dictionary, 2016)
motor cortex	the cortex of a motor area; also, the motor areas as a functional whole (Merriam-Webster's Medical Dictionary, 2016)
motor overflow	extraneous movement in a limb not involved in a motor action, typically observed in people with neurological impairments and in healthy children and adults during strenuous and attention-demanding tasks (Soska et al., 2012)

Appendix B Continued

Term	Definition
motor program	a stored representation, resulting from motor planning and refined through practice, that is used to produce a coordinated movement (APA Dictionary of Psychology, 2023)
multiple sclerosis	a demyelinating disease marked by patches of hardened tissue in the brain or the spinal cord and associated esp. with partial or complete paralysis and jerking muscle tremor (Merriam-Webster's Medical Dictionary, 2016)
myelination	the process of acquiring a myelin sheath (2) the condition of being myelinated (Merriam-Webster's Medical Dictionary, 2016)
myelin sheath	the insulating covering that surrounds an axon with multiple spiral layers of myelin, that is discontinuous at the nodes of Ranvier, and that increases the speed at which a nerve impulse can travel along an axon (Merriam-Webster's Medical Dictionary, 2016)
neural crosstalk	the way in which signal integration from multiple inputs in a response network affect a common biological output (Kennedy et al., 2014; Shea et al., 2016)
neuron	one of the cells that constitute nervous tissue, that have the property of transmitting and receiving nerve impulses, and that possess cytoplasmic processes which are highly differentiated frequently as multiple dendrites or usually as solitary axons, and which conduct impulses toward and away from the cell body (Merriam-Webster's Medical Dictionary, 2016)
pattern storage	see *motor program*
parietal cortex	see *parietal lobe*
parietal lobe	the middle division of each cerebral hemisphere that is situated behind the central sulcus, above the sylvian fissure, and in front of the parieto-occipital sulcus and that contains an area concerned with bodily sensations (Merriam-Webster's Medical Dictionary, 2016)
parieto-	parietal and (Merriam-Webster's Medical Dictionary, 2016)
parieto-occipital	of, relating to, or situated between the parietal and occipital bones or lobes (Merriam-Webster's Medical Dictionary, 2016)
perceptual	of, relating to, or involving perception esp. in relation to immediate sensory experience (Merriam-Webster's Medical Dictionary, 2016)
perceptual-motor system	the integration of sensory experience into the action of the motor system (Kurtz & Lee, 2003)

Appendix B Continued

Term	Definition
perturbation	a disturbance of motion, course, arrangement, or state of equilibrium (Merriam-Webster)
phase	a point or stage in the period of a periodic motion or process (as a light wave or a vibration) in relation to an arbitrary reference or starting point in the period (Merriam-Webster's Medical Dictionary, 2016)
physiology	the organic processes and phenomena of an organism or any of its parts or of a particular bodily process (Merriam-Webster's Medical Dictionary, 2016)
posterior	situated at or toward the hind part of the body (Merriam-Webster's Medical Dictionary, 2016)
precentral gyrus	the gyrus containing the motor area immediately anterior to the central sulcus (Merriam-Webster's Medical Dictionary, 2016)
prefrontal cortex	the gray matter of the anterior part of the frontal lobe that is highly developed in humans and plays a role in the regulation of complex cognitive, emotional, and behavioral functioning (Merriam-Webster's Medical Dictionary, 2016)
pronation	rotation of an anatomical part towards the midline as (1) rotation of the hand and forearm so that the palm faces backwards or downwards (b) rotation of the medial bones in the midtarsal region of the foot inward and downward so that in walking the foot tends to come down on its inner margin (Merriam-Webster's Medical Dictionary, 2016)
proprioception	the reception of stimuli produced within the organism (Merriam-Webster's Medical Dictionary, 2016)
pyramidal cell	any of numerous large multipolar pyramid-shaped cells in the cerebral cortex (Merriam-Webster's Medical Dictionary, 2016)
pyramidal tract neurons	corticospinal tract (Merriam-Webster's Medical Dictionary, 2016)
representation	that which stands for or signifies something else; in cognitive psychology, a mental representation (American Psychological Association, 2023)
scaling	a graduated series or scheme of rank or order (Merriam-Webster's Medical Dictionary, 2016)
sensorimotor	of, relating to, or functioning in both sensory and motor aspects of bodily activity (Merriam-Webster's Medical Dictionary, 2016)
sensory area	an area of the cerebral cortex that receives afferent nerve fibers from lower sensory or motor areas (Merriam-Webster's Medical Dictionary, 2016)

Appendix B Continued

Term	Definition
somato-	(1) body (2) somatic and (Merriam-Webster's Medical Dictionary, 2016)
somato-motor cortex	the somatosensory and motor cortex (Caeyenberghs et al., 2011; Eliassen et al., 1999; Jäncke et al., 2000)
subregion	a subdivision of a region (Merriam-Webster)
supination	(1) rotation of the forearm and hand so that the palm faces forward or upward, and the radius lies parallel to the ulna; also, a corresponding movement of the foot and leg (Merriam-Webster's Medical Dictionary, 2016)
sulcus	furrow, groove, especially a shallow furrow on the surface of the brain separating adjacent convolutions (Merriam-Webster's Medical Dictionary, 2016)
supplemental motor area	located on the medial aspect of the hemisphere, exerts modifying influences upon the primary motor area and appears to be involved in programming skilled motor sequences (Britannica)
sylvian fissure	a deep fissure of the lateral aspect of each cerebral hemisphere that divides the temporal from the parietal and frontal lobes (Merriam-Webster's Medical Dictionary, 2016)
synapse	the place at which a nerve impulse passes from one neuron to another (Merriam-Webster's Medical Dictionary, 2016)
task-switching	a procedure in which the participant switches between two or more tasks, typically according to a regular schedule in experimental situations (American Psychological Association, 2023)
temporal	of or relating to the sequence of time or to a particular time (Merriam-Webster, 2023)
transcallosal	passing through the corpus callosum (Merriam-Webster, 2023)
transcranial magnetic stimulation	a noninvasive technique for stimulating brain neurons that uses an electromagnetic coil usually placed on the scalp to produce magnetic fields which generate electric currents in specific areas of the brain especially to measure and map brain function and to treat depression and neuropathic pain (Merriam-Webster's Medical Dictionary, 2016)
transfer	the carryover or generalization of learned responses from one type of situation to another (Merriam-Webster's Medical Dictionary, 2016)

Appendix B Continued

Term	Definition
traumatic brain injury	an acquired brain injury caused by external force (as a blow to the head sustained in a motor vehicle accident or a bullet entering through the skull) (Merriam-Webster's Medical Dictionary, 2016)
unimanual	of or relating to one hand, or executed with one hand (Merriam-Webster)
ventral	being or located near, on, or toward the front or anterior part of the human body (Merriam-Webster's Medical Dictionary, 2016)
ventral medial wall	the surface of the brain located toward the spine and the body midline (Stephan et al., 1999)
visual capture	a phenomenon where visual information about a limb dominates one's proprioceptive perception of the limb's position (Brandes et al., 2017)
visuospatial	relating to or denoting the visual perception of the spatial relationships of objects (Oxford)
white matter	neural tissue especially of the brain and spinal cord that consists largely of myelinated nerve fibers bundled into tracts, has a whitish color, and typically underlies the gray matter (Merriam-Webster's Medical Dictionary, 2016)

Appendix C

Polyrhythm Tempo Guide

Fast Hand Tuplet	Tempo Threshold (bpm) [a]
1	360
2	180
3	120
4	90
5	72
6	60
7	51.4
8	45
9	40
10	36

Appendix C Continued

Fast Hand Tuplet	Tempo Threshold (bpm) [a]
11	32.7
12	30
13	28
14	26
15	24

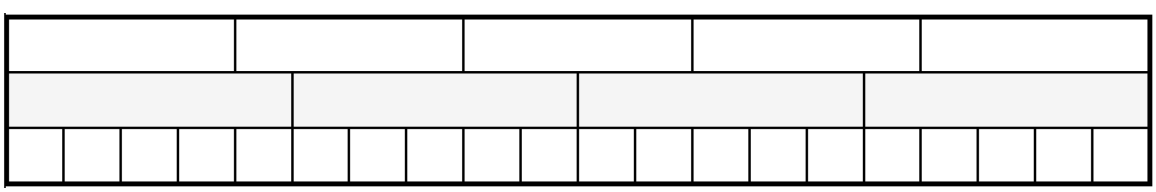
Note. The numbers in the left column represent the tuplet integer played by the fast hand in a polyrhythm, and the numbers in the right column represent tempos, in beats per minute (bpm), at which the performer should no longer attempt to perceive individual notes for timing accuracy. For example, a 4:3 polyrhythm should undergo this perceptual shift at a tempo of 90 beats per minute because the fast hand plays a four-tuplet.

[a] The tempo threshold is determined by dividing 360 [b] by the fast hand tuplet integer.

[b] The tempo of 360 was determined using Bogacz's (2005) finding that cognitive monitoring occurrs until approximately six notes per second (a six-tuplet at a tempo of 60 beats per minute).

Appendix D

Alternate Visual Representation of a 5:4 Polyrhythm



Note. The first row represents timing of the fast hand, the second row represents timing of the slow hand, and the third row represents the LCM.

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Christian Clay Swafford

EDUCATION

Master of Music in Performance: University of Tennessee (Knoxville, TN) 2018—2020

Bachelor of Music in Education: University of Tennessee (Knoxville, TN) 2014—2018

RECENT PROFESSIONAL EXPERIENCE

Administration / Leadership

Graduate Teaching Assistant — University of Kentucky Percussion Studio 2022—2023

Graduate Teaching Assistant — University of Kentucky Musicology Department 2022

Battery Coordinator — 4th Wall Performing Arts, Percussion Independent World (PIW) class in Winter Guard International (WGI) circuit 2021—2022

Administrator — Cue Percussion 2020—2022

Masterclasses / Residencies

Clinician — Lecture Recital: Polyrhythmic Pathways (Carl Lampert Recital Hall, University of Kentucky College of Fine Arts, Lexington, KY) Apr. 2023

Judge and Clinician — East Tennessee State University Percussion Ensemble Festival (Johnson City, TN) Mar. 2023

Clinician — Ownership as a Vehicle to Performative Confidence (Carl Lampert Recital Hall, University of Kentucky College of Fine Arts, Lexington, KY) Oct. 2022

Cue Percussion Quartet

Performer and Audio Production — Inside Out Sprouts! Season 4 Apr. 2021

Composer, Performer, and Audio/Video Production — Tag Project 2020—2021

Guest Artist — Austin Percussion Festival, TX Dec. 2020

Composer and Performer — Social DisDance Nov. 2020

Composer and Performer — Neuroscience Course Content (Syracuse, NY) Sep. 2020

Composer, Performer, and Audio Production — The Crossword Experiment Aug. 2020

Composer, Performer, and Audio Production — Inside Out Sprouts! Season 1 Jul. 2020

Performer — *June* (Virtual Edition) Apr. 2020

Composition / Design

Composer — *Barrier,* premiered at the Austin Percussion Festival, TX 2020

RECENT TEACHING

Adjunct Professor of Percussion — Eastern Kentucky University (Richmond, KY) 2023

Percussion Methods (MUC 157) at the University of Kentucky (Lexington, KY) 2022—2023
2023

Percussion Instructor — Woodford County High School (Woodford Co., KY) 2021—2023

Assistant Instructor in Performing World Music (MUS 130) at the University of Kentucky (Lexington, KY) 2021—2022

Snare Drum Technician — 4th Wall Performing Arts, PIW in WGI circuit (Bourbon Co., KY) 2021—2022

RECENT CREATIVE AND PERFORMING ACTIVITIES

International Performances

Performer — Big Ears Music Festival with Nief-Norf (Knoxville Botanical Gardens Arboretum, Knoxville, TN) Apr. 2021

World Percussion

Guest Artist — Luciano Medina Senior Recital (Otis A. Singletary Center for the Arts, Lexington, KY) Oct. 2021
- World premiere, *Why Not* by Michel Camillo, arr. Matthew Tremmel

Performer — Blue Steel (Sayre Christian Village, Lexington, KY) Jul. 2021

Orchestra

Section Percussionist — Lexington Philharmonic (Lexington, KY) 2022—Pres.

Regional Performances

Assistant Conductor and Performer — UK Percussion Ensemble (Otis A. Singletary Center for the Arts, Lexington, KY) Apr. 2023

Assistant Conductor — UK Percussion Ensemble (Otis A. Singletary Center for the Arts, Lexington, KY) Mar. 2023

Guest Artist — UK World Music and Dance Concert (Otis A. Singletary Center for the Arts, Lexington, KY) Nov. 2022

Assistant Conductor — UK Percussion Ensemble (Otis A. Singletary Center for the Arts, Lexington, KY) Oct. 2022

Director and Performer — Timber at the Arboretum: An Earth Day Celebration (The Arboretum State Botanical Garden of Kentucky, Lexington, KY) Apr. 2022

Guest Artist — Emily Durocher DMA Recital: Amid the Silence (Otis A. Singletary Center for the Arts, Lexington, KY) Apr. 2022

Soloist — Christian Swafford DMA Solo Recital (Otis A. Singletary Center for the Arts, Lexington, KY) Mar. 2022
- World premiere, *Box Truck Blues* by Peter Naughton

Guest Artist — Luciano Medina Senior Recital: grüve-toons (Otis A. Singletary Center for the Arts, Lexington, KY) Mar. 2022

Assistant Conductor — UK Percussion Ensemble (Otis A. Singletary Center for the Arts, Lexington, KY) Oct. 2021

Guest Artist — Emily Durocher DMA Recital (Otis A. Singletary Center for the Arts, Lexington, KY) Apr. 2021

Performer — UK Percussion Ensemble (Otis A. Singletary Center for the Arts, Lexington, KY) Apr. 2021

Guest Artist — Cue Percussion (Sandra G. Powell Recital Hall, Natalie L. Haslam Music Center, Knoxville, TN) Feb. 2021
- World premiere, *Painted Views* by Turner McCabe

Performer — UK Percussion Ensemble (University of Kentucky College of Fine Arts, Lexington, KY) Nov. 2020

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