THE ROUTLEDGE COMPANION TO EMBODIED MUSIC INTERACTION

Edited by Micheline Lesaffre, Pieter-Jan Maes, and Marc Leman

Routledge
Taylor & Francis Group
NEW YORK AND LONDON

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INTERACTIONS IN ENSEMBLE MUSIC PERFORMANCE

Empirical and Mathematical Accounts

Caroline Palmer and Anna Zamm

Introduction

The ways in which musicians coordinate their sound and actions in ensemble or "joint" performance has become a focus of much interest. As a rhythmic stimulus, music has the capacity to entrain individuals, thus facilitating their social interaction and communication. Novel techniques for measurement of sound as well as movement have led to an explosion of data from performing musical ensembles. Less clear is a guiding theory to explain the resulting Big Data. Most scientific studies of music performance have focused on individual differences in solo performance; those include differences based on attention, auditory imagery, motor imagery/simulation, memory retrieval, motor fluency, and feedback monitoring. Fewer of these factors have been examined in the context of performing ensembles.

The recent surge of interest in temporal coordination among performing musicians requires a theoretical reorientation to account not only for individual differences within performers but also for the complex interactions that arise among performers. We describe in this chapter empirical measures of musical ensembles—two or more individuals engaged in a musical task. The majority of empirical studies of ensemble performance to date have focused on Western tonal classical music and, in particular, on small ensembles (duets and quartets). Additional studies have examined how individuals perform with a computer-generated performance or with a recording (D'Ausilio, Novembre, Fadiga, & Keller, 2015). In this chapter we focus on the natural case of human ensembles, which permits temporal adaptation among all performers. The first section, "Empirical accounts of coordination," reviews empirical findings of extrinsic and intrinsic factors of temporal coordination in ensemble music performance. The second section, "Mathematical models of group coordination," focuses on mathematical theories of temporal coordination among performing musicians. Finally, we discuss future directions toward unifying models of temporal coordination in ensemble music performance.

Empirical Accounts of Coordination

The temporal coordination that arises in musical ensembles is quite complex; in addition to influences from auditory cues, coordination can be influenced by visual cues, ensemble size, social relationships, and other interpersonal factors. The scientific literature on temporal coordination among group members has focused on intentional and spontaneous tasks. Most musical ensembles in Western tonal traditions have an explicit intention to coordinate their parts in time; however, coordination can arise spontaneously as well. The study of group coordination across many movement tasks often distinguishes between *spontaneous coordination* that emerges without intention and *intentional* (goal-directed) coordination. Examples of spontaneous coordination include how people adjust their walking stride, begin to applaud together, or perform with the same style when playing the same part in the same section of an ensemble. Examples of intentional coordination between people include throwing and catching a ball, turn-taking in conversational speech, or conductor-orchestral member leader-follower relationships in setting a tempo. Spontaneous forms of coordination are thought to emerge from interactions among individuals that are driven by *intrinsic* factors, internal to individuals. In contrast, intentional forms of coordination are often posited to arise from factors *extrinsic* or external to each individual. We discuss intrinsic factors and extrinsic factors that may influence temporal coordination in ensemble performance.

Extrinsic Factors

Influence of Musical Structure

The rhythmic or tonal complexity that arises between performers' parts can influence temporal coordination in ensemble performance. Often, the rhythmic complexity influences the amount of asynchrony measured between parts (Goebl & Palmer, 2009; Loehr & Palmer, 2009). Greater rhythmic complexity, defined by the rhythmic ratio formed by inter-player tone durations, was associated with more variable synchronization of tone onsets and more variable inter-onset intervals. The increase in difficulty can be attributed to increased perceptual, anticipatory, and/or motor complexity of the task.

Tonal relationships between parts can also affect temporal coordination. Loehr and Palmer (2011) tested the tonal complexity arising between two parts in piano duet performance by altering the musical composition; in one setting, performers played a homophonic duet in which the tonal and rhythmic relations were as similar as possible between the parts. In another setting, the performers played a polyphonic duet in which the tonal and rhythmic relations differed between the parts. The total number of tone onsets in each part was held constant across the homophonic and polyphonic arrangements. Comparison of the temporal patterning showed a similar right-hand/left-hand pattern across bars for both solo and duet performances; interestingly, the pattern was modulated differentially for the homophonic and polyphonic parts, regardless of whether one or two people performed the right- and left-hand parts. Palmer and Loehr (2013) reported similar effects; pianists played two-part melodies in solo (two hands) or duet performances (each partner performed one part) with either simple or complex left-hand parts. The simple left-hand structure was associated with greater similarity of temporal patterning than the complex left-hand structure across both solo and duet performances.

Influence of Group Roles

Several types of group behavior display asymmetries among group members that arise as a function of the roles that members play, such as soloist-accompanist musician roles. Group roles can alter the equality or symmetry among members, which in turn can influence measures of coordination. Musical ensembles often have a leader whose role is to enable the group's goal of performing in synchrony by regulating the pace (tempo). In the first experimental study of temporal coordination between performing musician dyads, Goebl and Palmer (2009) discovered that leader-follower roles directly influenced synchronization. Each pianist took turns performing the melody or accompaniment in a piano duet; the pianist performing the melody part, the leader, was in charge of determining the tempo. Measures of signed asynchronies showed influences of leader-follower roles, with the leader's tone onsets tending to precede those of the follower. Manipulations of auditory feedback delivered over headphones to the pianists showed that the leader tended to be less influenced than the follower by the removal of feedback. Palmer, Spidle, Koopmans, and Schubert (2013) reported similar findings with duet vocalists, who sang a simple melody in unison or in a round (canonical form); each singer in the duet took turns as the leader, who was in charge of determining the tempo. The signed asynchronies showed that the leader's tone onsets tended to precede those of the follower. This leader-based asynchrony remained when the vocalists faced outward (in the absence of visual cues), suggesting the signed asynchrony findings were acoustically meaningful and not solely a visual cuing phenomenon.

Interestingly, when piano duettists are not assigned roles, their musical parts do not always show a consistent asynchrony in tone onsets. Loehr and Palmer (2011) studied duet pianists' ability to perform right-hand melodies when the left-hand accompaniment was performed by themselves or by their partner. The left-hand accompaniment was simple (homophonic style) or complex (polyphonic style). Mean asynchronies (right hand—left hand) were negative in solo performance, showing the melody part leading as found in other studies of solo performance (cf. Palmer, 1997). In joint performance, however, mean asynchronies were positive, indicating a left-hand lead on average. Temporal coordination measures (asynchronies and cross-correlations of inter-onset intervals between the parts) were influenced by individual differences between partners' spontaneous rates; partners who had similar spontaneous rates in solo performance were better synchronized and showed mutual adaptation to each other's timing during duet performances. Neither performer's spontaneous rates correlated with the duet performance measures; it was the mismatch between the performers in each pair (relative differences) rather than the characteristics of either individual (absolute levels) that predicted the temporal characteristics of the joint performance.

Larger groups also contain leader-follower relationships, sometimes with nested hierarchies, such as conductors signaling to large orchestras that contain sections with sub-leaders (such as a first violin in a violin section). Fewer studies have investigated timing relationships influenced by these nested group roles. Timmers, Endo, Bradbury, and Wing (2014) analyzed acoustic measurements of members of a string quartet performance of a Haydn quartet; within string quartets, artistic leadership is often attributed to the first violinist, who often performs the primary theme. The first violin's tone onsets tended to yield negative asynchronies relative to the tone onsets of the remaining three string quartet players.

D'Ausilio et al. (2012) recorded conductors' baton movements and violinists' bow movements during joint performance. As the conductor-to-musician influence of kinematic movements increased, the musician-to-musician movement coordination decreased, suggesting that a hierarchical unit had formed. In a further study of conductors' gestures, Luck and Toiviainen (2006) captured the movements of a conductor's baton during a 20-minute ensemble performance to test the hypothesis that musicians would synchronize primarily with the auditory cues of their fellow performers, while following the visual cues of the baton. The timing of the ensemble performance was cross-correlated with the conductor's baton motion. The ensemble's performance exhibited higher cross-correlations and smaller lag between the conductor's baton movements for pieces designated as having a clear beat. These real-world situations of ensemble performers who synchronize with a section leader or conductor while hearing other performers suggest that sensorimotor integration of one's own performance within an acoustic/visual environment becomes more complex than simple models to date can capture.

Intrinsic Factors: Endogenous Rhythms

Intrinsic factors associated with *spontaneous* coordination also play a role in temporal coordination between performing musicians. One example of an intrinsic factor that affects a variety of behaviors in both plants and animals, ranging from metabolic activity to sleep, walking, and other rhythmic activities, is endogenous frequencies: internal rhythms that exist in the absence of external stimulation (Bunning, 1956; von Holst, 1929). Endogenous rhythms are exhibited in musicians' spontaneous performance rates and show individual differences. Loehr and Palmer (2011) reported a correlation between individual pianists' tendency to speed up or slow down while performing a melody following an initial metronome cue, and their tendency to lead (negative asynchrony) or follow (positive asynchrony) a partner's tone onsets when performing duets. Zamm, Pfordresher, and Palmer (2015) tested whether individual differences in the spontaneous rates of solo music performance (in the absence of a metronome) were correlated with the degree of synchronization in joint performance with a partner. If endogenous rhythms entrain to auditory rhythms present in the environment, then temporal coordination of duet performance may be constrained by differences in performers' endogenous rhythms: the greater that difference, the larger the asynchronies that may be observed. That is indeed what Zamm et al. (2015) found; the larger the differences in spontaneous rates of solo performance, the larger the signed asynchrony (faster minus slower performer) in duet performance. In a subsequent study, Zamm, Wellman, and Palmer (2016) showed that pianists' spontaneous rates were consistent across musical pieces, across time points (up to one year), and across arm, hand, and finger movements (melodies played with the right or left hands). When those pianists were paired with a duet partner who was matched or mismatched for their spontaneous rates, the resulting absolute asynchronies and the standard deviation of the signed asynchronies (a measure of stability) were greatest for the mismatched group. None of the pianists' individual differences, such as individual spontaneous performance rates or years of musical training, accounted for the asynchrony difference between groups.

Musicians' spontaneous performance rates, measured by mean tone duration or *period* (inverse of frequency), can be interpreted as natural frequencies of internal oscillations and represent stable modes of minimal energy expenditure or effort. Individual differences in these internal oscillations can influence synchronization accuracy with a metronome (Loehr & Palmer, 2011) and with another human (Zamm et al., 2015). Investigations of duet performances based on randomly paired individuals (Palmer et al., 2013; Zamm et al., 2015) and controlled pairings (Zamm et al.; 2016) have both yielded findings that differences in partners' spontaneous rates corresponded to the amount of adaptation needed to bring the partners into synchrony.

Mathematical Models of Group Coordination

Although there are few models to date of group coordination, two primary camps have provided mathematical formalisms for how *individuals* coordinate in time with an external stimulus. An *information-processing* view, which focuses primarily on intentional coordination, considers rhythmic synchronization as achieved through error correction mechanisms that identify discrete temporal disparities between internal clock mechanisms and external feedback, event by event (Vorberg & Wing, 1996; Wing & Kristofferson, 1973). A *dynamical systems* view holds that synchronization emerges spontaneously from a continuous nonlinear coupling of internal oscillations, such as endogenous rhythms, at periodicities similar to those present in external signals. In this view, temporal coordination arises in a self-organized fashion similarly for collections of neurons and for partners in joint coordination tasks (Kelso, 1995; Schöner & Kelso, 1988). Recent applications of these models to group coordination acknowledge that many types of group behavior display asymmetries among group members (such as teacher–student conversational roles or soloist–accompanist musician roles), but for mathematical simplicity, both model applications tend to assume *equality* (symmetry) among members (Kuramoto, 1997; Wing, Endo, Bradbury, & Vorberg, 2014).

Most models of sensorimotor synchronization among performing musicians assume that some kind of error correction occurs following perceived failures of temporal coordination. Those failures can arise as a function of perceived relative phase between tone onsets intended to be simultaneous (asynchrony) or as a function of perceived shortening or lengthening of inter-onset intervals or periods (lagging/leading in tempo). Further distinctions of asynchrony have examined the signed asynchrony, usually in cases in which group roles apply (leader/follower or faster/slower performer), the absolute or unsigned asynchrony (usually when no group roles apply), and the variance of the signed asynchrony (usually measured as standard deviation of the signed asynchrony). Although several possible explanations have been proposed for the often-replicated finding that musicians tend to exhibit a negative mean asynchrony when playing with a regular metronome (see Repp & Su, 2013; for a review), there is still no agreed-upon explanation for this relative phase discrepancy. As discussed in the following sections, different models make predictions for different measurements of temporal coordination, depending in part on whether they examine extrinsic (group roles) or intrinsic factors (endogenous frequencies).

Linear Phase Correction

A linear phase correction model of synchronization, first proposed for individual performers (Vorberg & Wing, 1996), was based on the principle that asynchrony between tone onsets and metronome beats can be described as phase error, which is used by a performer to adjust the time interval leading up to the next tone onset in proportion to the preceding asynchrony. Time intervals are generated by an assumed internal timekeeper and corrected based on the perceived asynchrony multiplied by some correction strength or "gain" plus a noise term. Thus, correction gain is the size of the timing adjustments that performers make relative to the size of the asynchrony they perceive. Recently, the error correction model was extended to predict increased (proportional) correction gains for group synchronization as the group size increases (Wing et al., 2014). The linear phase correction model was expanded to quartet synchronization with a set of linear regression equations that allowed for correction gains applied by each performer for the asynchrony computed with each other performer, and random noise terms identified with each internal timekeeper. An optimal correction gain of 1/N (N = group size), based on simulations, was assumed to minimize asynchrony variance, the model's stability metric. Applications of the model to two skilled string quartet performances of an isochronous Haydn quartet passage produced correction gains that suggested the first violin adjusted less to other performers in one quartet than did the other performers adjust to the first violin, consistent with a leadership role. In addition, in both quartets, the cello player's correction gains were larger than for other players, suggesting this player adjusted more to other players than vice versa. Recent extensions of the linear phase correction model (Jacoby, Tishby, Repp, Ahissar, & Keller, 2015), using a generalized least-squares method to estimate model parameters, reduces error and bias in the parameter estimates, providing a generalized form of the model for use with ensemble synchronization research.

Nonlinear Oscillators

A different type of mathematical model for temporal coordination in music performance has developed from the idea that an individual responds to external stimulus rhythms with internal attentional oscillations (Large & Jones, 1999). This view assumes that an external rhythmic signal evokes intrinsic neural oscillations that entrain to the periodicities present in rhythmic sequences. Entrainment is a process by which two oscillating systems, which have different periods or natural frequencies when they function independently, assume the same period, or integer-ratio-related periods, when they interact. According to the dynamic approach, rhythmic motor behavior arises from one or more oscillations, which can be modeled by nonlinear differential equations. This model has been applied to account for listeners' rhythmic expectancies in temporally varying auditory events (Large & Jones, 1999), as well as to performers' abilities to track a changing metronome (Loehr, Large, & Palmer, 2011). It has also been applied to tracking live music performances, whose period and phase fluctuations are less predictable (Large & Palmer, 2002).

Nonlinear oscillator models are often called intrinsic timing models because they assert that time is inherent in the neural dynamics. There are several mathematical models of how synchronization arises among biological oscillators. Kuramoto's (1984) mathematical model described synchronization as a change in phase in response to the phases of all other oscillators; this approach assumed equivalent coupling (equal influence) between oscillators. In order to model extrinsic influences such as group roles or changes in auditory feedback among musicians, we assume that inequalities must arise, as reflected in the coupling among oscillations. We consider these possibilities in the next section.

Comparisons

Loehr et al. (2011) addressed two distinctions between nonlinear oscillator models (Large & Kolen, 1994) and linear timekeeper models (Schulze, Cordes, & Vorberg, 2005), in a study of how pianists intentionally adjusted their tempo to match the period of a changing metronome. The first model distinction concerned the coupling (linear or nonlinear) between the timekeeper or oscillator and the stimulus sequence; the linear timekeeper model predicted that adaptation to a metronome that decreased or increased in tempo should have been precisely the same. In contrast, the nonlinear coupling of the oscillator model predicted that adaptation should be better for sequences that decreased rather than increased in tempo. The second distinction concerned the periodic or non-periodic coupling. The non-periodic coupling of the timekeeper model meant that when the timekeeper period is not close to the stimulus period, the timekeeper period will adjust until it synchronizes with the stimulus sequence (1:1 coordination). The periodic coupling of the oscillator model meant that when the oscillator period is not close to the stimulus period, the oscillator period adjusts to the same period as, or to an integer-ratio-related period of, the stimulus sequence (e.g., 2:1 coordination). The pianists' asynchronies showed faster (better) adaptation to a metronome that decreased in tempo. Furthermore, when the initial oscillator period and timekeeper intervals of the model were set so that the events were produced on the eighth-note beats (2:1 coordination), only the oscillator model was able to maintain coordination in response to changes in metronome rate. Thus, the dynamical systems model was better able to account for pianists' tempo changes in the context of non-isochronous musical rhythms and temporal fluctuations that typically arise in ensemble music performance.

Although these model comparisons were tested with individual musicians adapting to a changing metronome and not with groups of musicians, they demonstrate important differences in the underlying motivations behind the models, which have direct implications for larger musical groups. One such prediction is the weighting of roles and other explicit factors that differentiate the coupling among group members. Leader-follower relationships can be modeled with a uni-directional coupling of two oscillators; specifically, model simulations have generated adaptation and anticipatory behavior when a master (driver) chaotic system, based on a Rössler system, was coupled with a slave (driven) simple harmonic oscillator (Stepp & Turvey, 2010). The harmonic oscillator was coupled to its master using time-delay coupling (Pyragas, 1992, 1998), which is based on coupling strength and time-delay parameters. Whereas the driver oscillator receives feedback only about its own states, the driven oscillator receives feedback about the driver and its own behavior (at a time delay). Anticipation and adaptation arise through feedback from the driven system's previous states and information about the driver to which it is coupled. The degree of anticipation (negative asynchrony) of the slave system relative to the master thus depends on the parameters of time delay and coupling strength; in the absence of a delayed feedback term, the negative asynchrony of the slave-master does not occur. Stepp and Turvey (2010) argue that delay is in fact a necessary condition of a master-slave coupled system and serves a stabilizing effect on the limit cycle that applies across master and slave systems (Pyragas, 1992, 1998). The uni-directionally driven slave system thus anticipates its master, and the system demonstrates anticipatory behavior without the need for additional internal models. This interpretation of negative asynchrony, it is argued, makes the search for internal predictive models unnecessary, if negative asynchrony is viewed as a positive, stabilizing aspect rather than as a threat to successful control.

A dynamical systems approach interprets findings resulting from removal of auditory feedback as breaking the bi-directional coupling that normally forms between individuals in joint performance. When auditory feedback is removed from one performer, a transition to a uni-directional state typically occurs in which the partner whose feedback was *not* removed becomes the driver, setting the pace for their partner, whose behavior is driven by the driver's performance (Goebl & Palmer, 2009). A similar anticipatory pattern of the driven system has been noted when individuals are asked to play with a metronome (Loehr et al., 2011); a uni-directional coupled system emerges with the performer (the driven system) consistently showing a negative mean asynchrony relative to the metronome (the driver system). In the perspective of a uni-directional coupled system, the driver's behavior is anticipated by the driven system, which uses feedback about its own states to anticipate. Whether and how changes in coupling arise with leadership, auditory feedback, and intrinsic factors specific to individuals remains to be determined. This is a promising line of mathematical modeling for temporal coordination in large musical ensembles.

Recent measures of duet piano performance (Demos, Wanderley, & Palmer, 2015) tested the influences of uni-directional coupling caused by auditory feedback removal on temporal synchronization. Two pianists each performed one part while auditory feedback from one or both of the musical parts was removed from both pianists' headphones at an unpredictable time, and the pianists were instructed to continue to play. Feedback returned after an unpredictable short period. When auditory feedback from one musical part was removed, the asynchrony between parts changed: Tone onsets of the pianist whose part was removed preceded the tone onsets of their partner, consistent with the interpretation of the driven system (the person whose actions were removed) anticipating the actions of the driver (the person whose actions were retained). In addition, asynchronies became more variable when the feedback from one or both parts was removed. The same feedback manipulations applied to the solo performances showed no effect of auditory feedback removal on mean asynchronies between parts or on the temporal variability. These findings are consistent with the time-delay coupling predictions of anticipation in a uni-directional master-slave system (Pyragas, 1998, 2008; Stepp & Turvey, 2010). When musicians performed together under normal circumstances, they did so as a coupled bi-directional system; the removal of one performer's auditory feedback induced a uni-directional state in which the driven system (whose feedback is absent) anticipates the driver (whose feedback is present) (Demos et al., 2015).

Models of Larger Ensembles

Other mathematical models have addressed larger temporal relationships in musical ensembles, including conductor–section leader–performer relationships. Drew, Dolch, and Castro (2015) present a mathematical model for the phase and tempo of performers with a conductor, based on the idea that each performer's response equals the stimulus (conductor, other performers) times the performer's sensitivity, with the addition of noise. A sensory factor represents an internalized tempo of each performer, and a motor factor models their physical response. The model takes an internal tempo setting and predicts when the next response should occur. The model assumes that the performers change tempo in response to a combination of stimuli with competing tempi (the conductor, other performers in a section, another dominant section leader, etc.). Thus, the discrete time model motivates a stochastic differential equation model for each performer in a large ensemble (Drew et al., 2015). The linear difference equations for phase and tempo plus an error term due to noise result in solutions for tempo correction by a performer who strays too far from the conductor's tempo. The model suggests that performance in sections has an added source of error due to noise that is focused on the sections themselves, which become a competitor to the conductor in setting the tempo. A dominant performer may be better able to follow the conductor's tempo, but s/he will also be subject to noise-induced error. The average performer will hear and respond to noise in the signal of a dominant performer; that is, the dominant performer competes with the conductor for the attention of the average performer. Thus, Drew et al. (2015) allows for inequalities in sensitivity of each performer to another; one performer may be more sensitive to (respond more to) their partner than vice versa, or specific performers' contributions may be considered dominant.

D'Ausilio et al. (2012) also modeled the timing of a conductor and musicians, based on linear regression modeling of stochastic processes with Granger causality metrics. They tested whether conductors' movement kinematics of the baton were associated with string players' bowing performance and if this influence affected inter-musician interactions. Eight violinists played familiar musical pieces with two conductors. The Granger causality values for each conductor–violinist pair measured whether past movements of the conductor's baton influenced the violinists' current bow movements above and beyond past values of the musicians' bow movements alone. These values were compared with the Granger causality values for each musician–musician pair within the same ensembles. The two conductors' movements showed different degrees of influence on the musicians' bowing, and the inter-musician average interaction strength changed as well. Although the role of specific bowing movement patterns was not elucidated within the D'Ausilio et al. (2012) study, the Granger causality pattern among conductors' and violinists' movements suggested that a network of interactions existed among the members of larger groups.

Conclusions

Empirical measures of the temporal dynamics underlying ensemble music performance have focused predominantly on dyadic interactions and have uncovered the influence of both *intrinsic* and *extrinsic* factors that influence synchronization. *Extrinsic* factors include tonal and rhythmic relationships that arise between performers' parts, and group roles such as leader/follower roles that influence synchronization of tone onsets between performers. *Intrinsic* factors include musicians' endogenous rhythms, measured as spontaneous performance rates, which promote synchronization of tone onsets among musicians with similar endogenous rhythms. Finally, *intrinsic* factors can modulate *extrinsic* factors; leadership behavior, for example, is more pronounced when leaders' endogenous rhythms are faster than those of followers (Palmer et al., 2013; Zamm et al., 2015). The nature and extent of these interactions remains an avenue for future exploration.

Mathematical models of temporal coordination have recently been expanded to capture the more complex dynamics of musical ensembles, including their application to inter-musician interactions in non-Western ensemble performance. Clayton, Sager, and Will (2005) applied principles of linear timekeeper and nonlinear dynamics to analyses of rhythms arising in native African songs and Australian songs. More recently, Polak, London, and Jacoby (2016) examined Malian djembe drumming trios and quartets to capture the temporal coordination arising as complex rhythms formed among the parts. These applications can shed light on conditions under which the complex rhythms of non-Western musical forms may be easier to perform in groups than in solo performance.

Another application of mathematical models has been to capture the social relationships that arise in group behavior. Linear models of ensemble timing have been applied to some leader/follower relationships in string quartets, suggesting potential for explaining the influence of some *extrinsic* factors—such as assigned group roles—on ensemble coordination. Dynamical models of coordination have been successful in uncovering the influence of *intrinsic* factors, such as endogenous rhythms on synchronization. A remaining challenge is to integrate linear and dynamic accounts of coordination. For example, can *extrinsic* influences be modeled by dynamical systems, and can intrinsic influences be modeled by linear systems? Unification of the different models and factors is an important step for understanding the complexity of temporal dynamics in ensemble music performance.

Acknowledgements

We thank Frances Spidle for comments on an earlier draft. This work was supported by NSERC Grant 298173 to Caroline Palmer and by FQRNT doctoral grant PBEEE to Anna Zamm.

References

Bunning, E. (1956). Endogenous rhythms in plants. *Annual Review of Plant Physiology*, 7(1), 71–90.

Clayton, M., Sager, R., & Will, U. (2005). In time with the music: The concept of entrainment and its significance for ethnomusicology. *European Meetings in Ethnomusicology*, *11*, 3–142.

D'Ausilio, A., Badino, L., Li, Y., Tokay, S., Craighero, L., Canto, R., . . . Fadiga, L. (2012). Leadership in orchestra emerges from the causal relationships of movement kinematics. *PLoS ONE*, 7(5), e35757.

D'Ausilio, A., Novembre, G., Fadiga, L., & Keller, P. (2015). What can music tell us about social interaction? *Trends in Cognitive Sciences*, *19*(3), 111–114.

Demos, A. P., Wanderley, M., & Palmer, C. (2015). Auditory feedback perturbations disrupt synchrony in ensemble music performance. *Abstracts of the Psychonomic Society*, *21*, 161–162.

Drew, D., Dolch, K., & Castro, M. (2015). A model for tempo synchronization in music performance. *Siam Journal on Applied Mathematics*, *75*(6), 2540–2561.

Goebl, W., & Palmer, C. (2009). Synchronization of timing and motion among performing musicians. *Music Perception*, *26*(5), 427–438.

Jacoby, N., Tishby, N., Repp, B. H., Ahissar, M., & Keller, P. E. (2015). Parameter estimation of linear sensorimotor synchronization methods: Phase correction, period correction, and ensemble synchronization. *Timing & Time Perception*, *3*, 52–87.

Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior.* Cambridge, MA: MIT Press.

Kuramoto, Y. (1984). *Chemical oscillations, waves, and turbulence.* New York, NY: Springer.

Kuramoto, Y. (1997). Phase- and center-manifold reductions for large populations of coupled oscillators with application to non-locally coupled systems. *International Journal of Bifurcation and Chaos*, 7(4), 789–805.

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, *106*(1), 119–159.

Large, E. W., & Kolen, J. F. (1994). Resonance and the perception of musical meter. *Connection Science*, *6*(2–3), 177–208.

Large, E. W., & Palmer, C. (2002). Perceiving temporal regularity in music. *Cognitive Science*, *26*(1), 1–37.

Loehr, J. D., Large, E. W., & Palmer, C. (2011). Temporal coordination and adaptation to rate change in music performance. *Journal of Experimental Psychology: Human Perception & Performance*, *37*(4), 1292–1309.

Loehr, J. D., & Palmer, C. (2009). Subdividing the beat: Auditory and motor contributions to synchronization. *Music Perception*, *26*(5), 415–425.

Loehr, J. D., & Palmer, C. (2011). Temporal coordination between performing musicians. *Quarterly Journal of Experimental Psychology*, *64*(11), 2153–2167.

Luck, G., & Toiviainen, P. (2006). Ensemble musicians' synchronization with conductors' gestures: An automated feature-extraction analysis. *Music Perception*, *24*(2), 189–200.

Palmer, C. (1997). Music performance. *Annual Review of Psychology*, *48*(1), 115–138.

Palmer, C., & Loehr, J. D. (2013). Meeting of two minds in duet piano performance. In L. Bernstein & A. Rozin (Eds.), *Musical implications: Essays in honor of Eugene Narmour* (pp. 323–338). Hillsdale, NY: Pendragon Press.

Palmer, C., Spidle, F., Koopmans, E., & Schubert, P. (2013). Temporal coordination in vocal duet performances of musical rounds. In R. Bresin & A. Askenfelt (Eds.), *Proceedings of the Stockholm Music Acoustics Conference* (pp. 678–682). Berlin, Germany: Logos.

Polak, R., London, J., & Jacoby, N. (2016). Both isochronous and non-isochronous metrical subdivision afford precise and stable ensemble entrainment: A corpus study of Malian jembe drumming. *Frontiers in Auditory Cognitive Neuroscience, 10 (285).*

Pyragas, K. (1992). Continuous control of chaos by self-controlling feedback. *Physics Letters A*, *170*(6), 421–428.

Pyragas, K. (1998). Synchronization of coupled time-delay systems: Analytical estimations. *Physical Review E*, *58*(3), 3067–3071.

Pyragas, K. (2008). Coupling design for a long-term anticipating synchronization of chaos. *Physical Review E*, *78*(4), article 046217.

Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20*(3), 403–452.

Schöner, G., & Kelso, F. A. S. (1988). Dynamic pattern generation in behavioral and neural systems. *Science*, *239*(4847), 1513–1520.

Schulze, H.-H., Cordes, A., & Vorberg, D. (2005). Keeping synchrony while tempo changes: Accelerando and ritardando. *Music Perception, 22*(3), 461–477.
Stepp, N., & Turvey, M. (2010). On strong anticipation. *Cognitive Systems Research, 11*(2), 148–164.
Timmers, R., Endo, S., Bradbury, A., & Wing, A. M. (2014). Synchronization and leadership in string quartet performance: A case study of auditory and visual cues. *Frontiers in Psychology, 5*, 645.
von Holst, E. (1929). *The behavioural physiology of animals and man: The collected papers of Erich von Holst* (vol. 1). Miami, FL: University of Miami Press.
Vorberg, D., & Wing, A. M. (1996). Modeling variability and dependence in timing. In H. Heuer & S. Keele (Eds.), *Handbook of perception and action* (vol. 2, pp. 181–262). New York, NY: Academic Press.
Wing, A. M., Endo, S., Bradbury, A., & Vorberg, D. (2014). Optimal feedback correction in string quartet synchronization. *Journal of the Royal Society Interface, 11*(93), 20131125.
Wing, A. M., & Kristofferson, A. B. (1973). The timing of interresponse intervals. *Perception & Psychophysics, 13*(3), 455–460.
Zamm, A., Pfordresher, P. Q., & Palmer, C. (2015). Temporal coordination in joint music performance: Effects of endogenous rhythms and auditory feedback. *Experimental Brain Research, 233*(2), 607–615.
Zamm, A., Wellman, C., & Palmer, C. (2016). Endogenous rhythms influence interpersonal synchrony. *Journal of Experimental Psychology: Human Perception & Performance, 42*(5), 611–616.