

The Psychology of Music

Third Edition

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Academic Press is an imprint of Elsevier
32 Jamestown Road, London NW1 7BY, UK
225 Wyman Street, Waltham, MA 02451, USA
525 B Street, Suite 1800, San Diego, CA 92101-4495, USA

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British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-381460-9

For information on all Academic Press publications
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Typeset by MPS Limited, Chennai, India
www.adi-mps.com

Printed and bound in United States of America

12 13 14 15 16 10 9 8 7 6 5 4 3 2 1

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10 Music Performance: Movement and Coordination

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I. Introduction

Most thoughts of music performance revolve around experts: highly skilled musicians who spend several hours per day practicing, usually on a single instrument. Indeed, a fair amount of the research literature on music performance is focused on such cases. However, all humans are capable of making music to some degree. Behaviors such as clapping to a song, humming or even imagining a familiar melody, or swaying to a beat are common among individuals with and without musical training. These behaviors represent complex examples of auditory scene analysis, temporal expectancies, and other attentional and auditory memory-based psychological processes that underlie music performance.

Two major advances have occurred in measurement of music performance: the first is a focus on performers' motion, with motion-capture and video analysis techniques. Recent technological developments have made it possible to measure joint movements of musicians with small markers and no wires. The second advance is a shift in focus from the individual to the group. Musicians tend to perform in groups; only those who play multivoiced instruments such as piano or guitar tend to perform by themselves as much as with others. Thus, it is fitting that ensembles should be a focus of current research in performance. The theoretical question becomes, how do models of single-individual behavior scale up to interactions among individuals? Several intriguing lines of research, reviewed here, have begun to focus on this question.

This chapter discusses research on these two novel developments in performance research: (1) the role of musicians' movement and its relation to sounded performance and (2) ensemble performance (two or more performers). Each discussion is focused on the period since 2002 (for previous reviews of music performance, see Gabrielsson, 1999, and Palmer, 1997; for reviews of rhythm and timing see Honing, Chapter 9, this volume, and of singing see Sundberg, Chapter 3, this volume). The discussion of movement in performance is further divided into sections on sensorimotor integration, biomechanical influences, and the role of expressive gestures. The discussion of ensemble performance is further divided into sections

on the role of sensory feedback from oneself versus other performers, individual differences among ensemble members, and the complex real-world case of conducting.

II. Movement in Performance

There are several perspectives on the role of motion in music performance. One perspective is that a performer's motion during performance is shaped by psychological processes and task demands; these may include anatomical and physiological adjustments of the body to best manipulate the musical instrument, and sensorimotor adaptations designed to optimize sensory feedback (from proprioceptive, tactile, visual, or auditory inputs). Another perspective, advanced by Truslit (1938; translated by Repp, 1993), describes performers' motion as a spontaneous manifestation of the expression of "inner motion," the driving force of the music related to interpretation, which is shaped by experience and artistic form and is related to emotion, sensation of motion, and communication. This perspective is related to a body of research that treats performers' motions as gestures: movements that do not produce sound, but are related to the performers' intentions to shape the sound. These two perspectives on the role of motion in performance are described in this section.

Recent developments of motion capture systems allow researchers to record the precise spatial position of each body joint at each point in time, with small reflective markers whose position is recorded with infrared cameras. Motion capture methods include active systems (whose wired markers emit an infrared signal) and passive systems (whose wireless markers passively reflect light) to measure joint movements during performance with very fine temporal resolution (on the order of 10 ms). This method yields copious amounts of data that must be coordinated with the acoustic events, also sampled at high rates to permit fine temporal resolution. Traditional methods for reducing motion data to reasonable amounts involve filtering and smoothing techniques; however, some fine movements can be obscured or reduced with these methods.

Recent applications of functional data analysis techniques (Ramsay & Silverman, 2005) make it possible to retain the fine spatial information captured in limb movements and align that information with other data streams (such as other motion measurements or acoustic events) through a process called co-registration. Functional data analysis (FDA) methods are used to fit a continuous function, based on b-splines, to a higher-order derivative of the discrete data stream, in order to smooth a lower-order derivative such as the velocity or acceleration of finger movements (FDA techniques are described in more detail in Goebel & Palmer, 2008; Loehr & Palmer, 2007; Vines, Krumhansl, Wanderley, & Levitin, 2006). The continuous function can be resampled at a different rate than the original sampling rate, and realigned with other performances that may have originally contained different numbers of measurements, due to differences in tempo or

sampling rate. Another advantage that FDA methods offer is the identification and highlighting of motion landmarks that may be lost with the application of traditional filtering and smoothing methods. For example, FDA methods have been used to identify landmarks in finger acceleration trajectories when performers' fingers first touch the instrument keys; touch is considered an important form of sensory feedback and a critical technique in pedagogical theory of performance.

The majority of motion studies described in the next section apply FDA methods to performers' movement data to address three general research questions: how movement provides sensory information to guide performance (tactile and proprioceptive feedback), how biomechanical and anatomical constraints affect performance, and how motion reflects expressive performance goals. Each of these questions is considered in this section.

A. *Movement as Sensory Information*

Several lines of research suggest that finger motion provides important sensory feedback to guide musicians' timing. Tactile information in performers' finger movements during performance can affect the temporal accuracy with which pianists perform upcoming events. Goebel and Palmer (2008) measured pianists' finger trajectories toward the piano keys with a motion capture system; finger trajectories contained different types and amounts of kinematic landmarks at different performance rates. One landmark, a finger-key landmark, indicated a sudden large change in acceleration when the finger made initial contact with the key surface; this landmark occurred more often at fast performance tempi. Performances by pianists whose landmarks increased across performance tempi showed a positive relationship between increased tactile feedback from the current keystroke and increased temporal accuracy of the subsequent keystroke. Palmer, Koopmans, Loehr, and Carter (2009) examined the same finger-key acceleration landmarks in clarinet performance; unlike piano performance, the speed of finger movements toward clarinet keys does not influence the resulting loudness of the performance (breathing determines tone amplitude on wind instruments such as clarinet). Again, the researchers found that increased use of the finger-key landmarks across tempi yielded improved temporal accuracy in the subsequent tone onset. These studies suggest that sensory information that is available when musicians' limbs make contact with their instrument enhances the temporal accuracy of upcoming movements.

How does movement-related feedback interact with other sensory feedback in music performance? Normally, solo performance yields tightly coupled auditory and motor information from one's own feedback. In contrast, ensemble performance yields auditory information that can occur in the presence or absence of one's own motor movements. Thus, it is possible that skilled musicians, who are used to playing with others, may or may not be disrupted by the presence of auditory or motor information that intervenes with their self-produced performance. Loehr and Palmer (2009b) contrasted the effects of auditory and kinematic information on pianists' ability to perform music with a metronome. Pianists produced

musical melodies composed of quarter-note beats that were subdivided in different conditions with intervening eighth notes that the pianists either heard (auditory information), produced (motor information), both (normal performance), or neither (absence of eighth notes). Effects of auditory and motor feedback on quarter-note performance were measured in terms of the temporal accuracy and the finger movement trajectories, recorded with motion capture. Temporal asynchronies in performance were largest when motor or auditory sensory information was present; auditory information gave rise to the largest asynchronies. In contrast, only the production of movements (and not auditory feedback) influenced upcoming finger motions; changes in finger motion suggested biomechanical constraints of coupling between the fingers that produced successive movements. This decoupling of auditory and motor information demonstrated that the influence of sensory information on the timing of performance depends on its modality (auditory information affects timing most, but motor information does also) whereas motion trajectories are influenced only by motor information arising primarily from biomechanical constraints on sequential finger motion.

Another paradigm that demonstrates the importance of auditory-motor coupling is manipulations of altered auditory feedback. In particular, the deleterious effects of delayed auditory feedback (DAF) on the timing of music performance have been widely documented. Several theories try to account for the auditory-motor relationship implied by DAF; a movement-related account of DAF (Howell, 2004) claims that altered auditory feedback perturbs the timing of execution, while other theories attribute the disruption to the mechanisms responsible for the intersection of perception and action (MacKay, 1987), and not to movement per se. Yet another theory (event coding; Hommel, Musseler, Aschersleben, & Prinz, 2001) views the shared representation for perception and action as driven by planned action goals that are coded as expected perceptual outcomes. Pfordresher and Dalla Bella (2011) tested whether DAF causes worst disruption when it is timed to coincide with the upward movements of fingers (away from key targets) than with downward movements toward keys; this prediction was supported in an isochronous tapping task. Thus, these findings were more consistent with movement-based theories of auditory feedback disruption (Howell, Powell, & Khan, 1983) than with movement-independent explanations (MacKay, 1987).

Biomechanical and anatomical constraints on the motion of performers' limbs influence the degree to which a possible movement is independent of the effector used to create it. For example, differences in hand dexterity may influence the precision of force or timing that a musician produces. Despite the fact that musicians practice exercises designed to reduce biomechanical constraints on fingers and hands, strong finger interdependencies still exist even in highly skilled musicians. For example, finger movements that produce sequences of elements are often influenced by the finger movements that generate neighboring elements in the sequence, a musical form of coarticulation. Successive finger movements may also be constrained by biomechanical coupling factors that can contribute to lack of independence among physically adjacent fingers, including shared muscles and tendons. Loehr and Palmer (2007) contrasted cognitive influences of chunking with

influences of biomechanical coupling on physically adjacent fingers in piano performance. Pianists repeatedly tapped four-finger sequences that differed in terms of the chunks that formed subsequences and in the transitions among physically adjacent or nonadjacent fingers. Chunking influenced the timing of intertap intervals, regardless of the particular fingers used; the final tap of each chunk was lengthened and less variable relative to other taps. The particular fingers used in the task influenced peak finger heights, consistency of motion, and velocity–acceleration trajectories, regardless of chunking. Thus, cognitive constraints influenced timing primarily, whereas biomechanical factors mainly influenced motion trajectories.

Pianists' temporal accuracy may be influenced by sequential effects of preceding finger movements (Loehr & Palmer, 2009a). Sequential dependencies between finger movements, similar to coarticulation effects in speech, may influence both the timing and motion with which fingers move on keys. Loehr and Palmer (2009a) recorded skilled pianists tapping sequences in which a finger whose motion was more or less independent of other fingers' motion was preceded by a finger to which it was more or less coupled. Less independent fingers and those preceded by a more coupled finger showed larger timing errors and larger changes in finger motion that were related to the preceding finger's motion. Thus, the timing of sequence elements was not independent of the pianists' finger motions used to produce them. Furthermore, the interactions between timing and motion were stronger at faster tempi. Overall, these findings indicate that temporal accuracy in performance depends on the specific sequential dependencies between fingers and on the tempo of the performance.

Given that specific finger movements affect the timing of performance, it is perhaps not surprising that individual differences in finger movements can differentiate performers. Dalla Bella and Palmer (2011) captured the motion of pianists' fingers as they performed melodies from memory at different tempi. Pianists' finger velocity–acceleration profiles as the fingers approached keys were sufficiently unique to allow identification with a neural-network classifier that was trained on individual finger keystrokes. Classification success, based again on individual keystrokes, was higher for pianists with more extensive musical training, and only finger movements toward keys—not away from keys, or when fingers were “at rest” (awaiting their turn for keystrokes)—provided sufficient information to accurately identify individual pianists; these findings held across all fingers (performer differences transcended finger differences). These movement “signatures” may reflect unique goal-directed movement kinematic patterns that lead to individualistic sound, consistent with music pedagogical literature that claims differences in pianists' touch are important for successful performance (see Goebel & Palmer, 2008).

B. Movement as Expressive Gesture

Performers' movements also encompass non–sound-producing movements that appear to be tied to expressive goals. The term “expressive gestures” refers both

to acoustic cues that distinguish one performance of the same music from another and to motion cues of musicians' bodies and instruments that often highlight important aspects of a performance (Palmer, 1997; Wanderley, 2002). For example, visual cues such as the head and upper torso movements of performing pianists can be as effective as auditory cues in conveying the pianists' intended expressivity to viewers (Davidson, 1995; Vines et al., 2006). Piano performance, the focus of the majority of movement studies, offers a limited range of motion cues because of the fixed position of the instrument and the seated position of the performer; expressive movement is limited to the hands, upper torso, and head (Davidson, 2002). Although a wider range of performers' movements have been documented for mobile instruments such as string (Askenfelt, 1986, 1989), brass (Overholt et al., 2009), and wind instruments (Wanderley, 2002), only more recently has research addressed the relationship between those movements and acoustic features of instrumentalists' expressive performance (e.g., Godoy & Leman, 2010).

Delalande (1988) classified the possible gestures available to a musician into three basic categories: effective gestures, figurative gestures, and accompanying gestures. Effective gestures are those that actually produce sound, such as pianists' finger movements in keystrokes. Figurative gestures include sonic gestures perceived by an audience that have no direct correspondence to physical movement, such as timbral changes in an instrument. Accompanying or ancillary gestures are visible body movements that are not directly linked to sound production, such as pianists' head movements. Ancillary gestures can influence perceivers' judgments of recorded music performances. Davidson (1993) recorded violinists while they performed a musical excerpt in three different styles: projected (normal), deadpan, and exaggerated intents. Viewers then rated each performance as belonging to one of the three categories, after viewing a point-light display of the performers' motion, hearing the audio recording, or both. In some conditions (particularly deadpan performances), visual information alone provided better identification of expressive intent than sound alone. These findings suggest that motion carries at least some unique information about performers' expressive intent relative to the acoustic cues.

Although the relationship between musicians' expressive gestures that arise from sound and from motion has been investigated largely with stationary instruments such as piano and drums (Dahl, 2004; Davidson, 2002), a few studies have addressed performers' movements on nonstationary instruments. Wanderley (2002) compared ancillary gestures in clarinetists' performances of the same musical piece in a standard (normal) performance, an expressive performance (with full range of expression), and a performance in which clarinetists were instructed to move the instrument as little as possible. The performances were recorded with optical motion capture and the clarinet bell position was analyzed in *x* (horizontal), *y* (sagittal), and *z* (vertical) dimensions. This experiment suggested that the same performers used consistent movements within each expressive condition and larger movements in the more expressive conditions.

Palmer et al. (2009) examined clarinetists' bell movements as the clarinetists swayed to the music they were performing. The orientation of clarinetists' bell

position was higher near the ends of musical phrases and lower near the beginnings; the magnitude of the bell elevation corresponded to the amount of expressive lengthening of tone durations. The finding of increased bell elevation in exaggerated performances is consistent with Delalande's (1988) distinction of sound-producing gestures from ancillary (non-sound-producing) gestures. Palmer et al. found a correspondence between lengthened tone durations and bell elevation, suggesting that ancillary gestures of bell motion may reinforce salient acoustic events at phrase boundaries. This correspondence increased in exaggerated performances and decreased in inexpressive performances relative to normal expressive performances, consistent with previous findings that expressive timing changes near phrase boundaries are modulated by expressive instructions to performers (Kendall & Carterette, 1990; Palmer, 1989). The fact that bell elevation did not increase with tone intensities suggests that bell elevation does not arise directly from sound production goals. Several studies tie expressive acoustic intentions (Chagnon, Campbell, & Wanderley, 2005; Wanderley, Vines, Middleton, McKay, & Hatch, 2005) to patterns of bell movement, one of the largest sources of motion in clarinet performance.

Some aspects of musicians' movement suggest a reinforcement of the periodicities present in the music. Toiviainen, Luck, and Thompson (2010) examined musicians' body movements that synchronized with the periodic structures of the musical meter. The authors hypothesized that performers would move their bodies in synchrony with a musical beat at more than one hierarchical level within the meter (Palmer & Krumhansl, 1990). Musicians' movements were captured while moving freely to an instrumental blues progression in $\frac{4}{4}$ meter. A periodicity analysis of the estimated kinetic energy indicated movement components at periods of one, two, and four beats, consistent with the musical meter. Thus, several metrical levels were incorporated in the dancers' movements, although participants tended to incorporate only one metrical level at a time. Faster metrical levels were seen in movements of extremities (hands and arms) and slower periodicities in the central part of the body (torso). A similar approach was applied to formal dance; Naveda and Leman (2011) applied a topological gesture analysis to the dance of two professionals and two students, who performed Charleston and samba styles. Although there was a small number of dancers, the spatial positions of arms and feet tended to synchronize with the first and second beats in the beginners' styles; the hand gestures indicated a two-beat level, and other (larger) metrical levels were seen in the coordination of body gestures. Although these studies were limited in the type of music, dance, and number of performers, this approach to deriving aspects of musical structure from movement remains promising.

In sum, motion of individual performers can enhance sensory information to guide the timing and dynamics of performance, as well as to mark expressively important structural and emotional aspects of performance. Next I discuss the role of motion in ensemble performance, where the task demands of coordinating two or more sources of sensory information and actions are much larger.

III. Ensemble Performance

Studies of psychological aspects of performance, ranging from reading notation (Brodsky, Kessler, Rubinstein, Ginsborg, & Henik, 2008; Sloboda, 1984) to skill learning (Ericsson, Krampe, & Tesch-Römer, 1993) to memory retrieval (Chaffin & Imreh, 2002; Palmer, 2005; Palmer & Pfordresher, 2003), have focused almost exclusively on the individual performer; yet, most performance occurs between musicians in groups, from duets to large orchestral ensembles. Successful performance requires individuals to adapt to the flow of the ensemble in their timing, dynamics (loudness), and timbre. Ensemble performance quickly becomes an expanded problem of sensorimotor integration: how the brain processes multiple sensory inputs (sensation) and maps them to outputs (action). How is the motor system involved in perception? How is the auditory system involved in production? These questions are critical in the realm of ensemble performance, in which musicians must adapt quickly to the sensory information from their own performance and that of other ensemble members. This problem has been encountered in other branches of behavior but is especially salient when split-second timing delays can wreak havoc on group performance.

Few empirical studies of ensemble performance were reported before 2002, but a trend has started with current technological advances in group measurement in acoustics (such as spherical array techniques) and in motion (including motion capture). One of the earliest studies reported auditory measurements of wind and string trios (Rasch, 1979) that showed that the performer playing the main melodic line sounded their tone onsets 10 ms earlier than the other parts. Shaffer's (1984) analysis of tones onsets in piano duets documented how the other members' performance timing caused adaptation by individual performers, while maintaining their individual roles such as "leader" and "follower." Seminal studies of solo and choral singing have documented changes in articulation, phonation, and overall sound level when singers perform together in ensembles (Rossing, Sundberg, & Ternstrom, 1986; see Chapter 3, this volume). More recent studies have focused on computer-accompanied performance by individual musicians who perform to a metronomic beat. In ensemble performance, however, one adapts against a variable tempo generated by other ensemble members who may in turn be adapting to each other. I focus next on these cases.

A. *Sensory Feedback in Ensembles*

Temporal correction in tapping tasks in response to changes in the timing of an auditory stimulus such as a metronome has been modeled with two processes: phase and period correction. Phase correction is thought to be automatic, whereas period correction is under cognitive control. Although this account of temporal coordination has been tested with tapping tasks (Konvalinka, Vuust, Roepstorff, & Frith, 2010; Large, Fink & Kelso, 2002; Repp, 2001; Semjen, Schulze, & Vorberg, 2000) and more recently with solo music performance with a metronome (Loehr,

Large, & Palmer, 2011), it has not been applied to ensemble performance yet, probably because of the computational complexity of the task. An alternative account of temporal correction by ensemble performers has been proposed, based on measurements of string ensembles. Moore and Chen (2010) tested string quartet members' ability to produce rhythmic groups of 16th-note sequences while motion sensors were attached to their elbows in order to measure bowing motions. Measurements of the angular velocity of the right forearm (the bowing arm) of the violist and violinist, who produced the 16th-note passages, indicated a high degree of synchrony (as measured by cross-correlations between successive down-bowed intervals), even while the tempo (frequency) of the bow strokes shifted across the musical performance; thus, this finding indicated a high degree of coupling between the string players. The authors modeled each string player's timing patterns as an alternating renewal process, in which the intervals between successive down-bows were drawn independently and randomly from two alternate distributions having longer and shorter means. The same was true for the up-bows, whose interval lengths were not the same as those for the down-bows. This approach was based on motion capture measurements of the bowing arm; it is not clear whether an alternating process could account for interonset intervals whose movements differed from the up-down pattern of bowing movements (such as pianists' successive keystrokes).

Structural relationships between the musical parts that musicians must coordinate also influence the timing of that performance. Palmer and Loehr (2012) compared solo and duet piano performances of two-part music in which the structure of the left-hand part (accompaniment) was designed to be simple or complex in melodic contour, in required hand movements, and in its relation to the right-hand melody. Tempo measures indicated that compositions with more complex structural relationships were performed more slowly than those with simple structural relationships, regardless of whether the performance was by a single (solo) performer or by two performers (duet). Furthermore, the performance tempi for the right-hand part (performed by the same pianists) in the solo and duet performances were highly correlated for the musical works that contained simple structural relationships but were not correlated for the complex structural relationships. Motion capture measurements of the right-hand finger movements indicated greater preparatory constraints of coordinating two limb movements in solo performance than in duet performance. Thus, the timing parameters of music performance reflected structural relationships in similar ways in the solo and duet performances, whereas the motion parameters revealed task-specific demands of multilimb coordination.

Familiarity with the musical material or style can influence temporal coordination. Keller, Knoblich, and Repp (2007) had skilled pianists record one part from unfamiliar duets; later, they performed the alternate part in synchrony with a recording of their performance of the first part or with another pianist's recording of that part. Although this task is not duet performance but instead playing along, the variability in the synchronization timing measures indicated the pianists were better at synchronizing with their own performance than with others. A later recognition test indicated that pianists identified their own performances better than

chance. The authors attribute this finding to a mental simulation of the other pianists' part; general differences in playing style may also contribute to this difference. Subsequent experiments (Repp & Keller, 2010) indicated that pianists were better at detecting temporal deviations in their own (self-generated) performance than in another pianist's performance, but only if that deviation was placed in a position that differed between self- and other-generated performances. Thus, personal playing style may influence the ability to generate temporal expectations that guide synchronization.

Several studies of ensemble performance document how performers adapt their coordination with other performers in the face of altered auditory feedback. Goebel and Palmer (2009) measured piano duets in which the pianist playing the upper part was designated the leader and the other pianist was the follower. They received full auditory feedback, one-way feedback (leaders heard themselves while followers heard both parts), or self-feedback only. In addition, the upper part contained more, fewer, or equal numbers of notes relative to the lower part. Temporal asynchronies between tone onsets notated as simultaneous increased as auditory feedback decreased: The pianist playing more notes preceded the other pianist, and this tendency increased with reduced feedback. Cross-correlations between the interonset intervals of the two parts suggested bidirectional adjustments during full feedback despite the leader/follower instructions, and unidirectional adjustment only (leader influencing follower) during reduced feedback. Motion capture analyses, based on markers placed on the heads and fingers of the pianists, indicated that leaders raised fingers higher and pianists' head movements became more synchronized as auditory feedback was reduced. Similar findings from Keller and Appel (2010) indicated effects on duet pianists' motion of removing visual contact between the two pianists. Asynchronization between tone onsets notated as simultaneous was correlated with the amount of cross-coordination lag in the pianists' body sway; the larger the asynchrony between pianists, the larger the lag between their frontward body sway patterns, as measured by their shoulder positions. Overall, these studies suggest that performers use alternative forms of sensory information more when some sensory information is removed.

Which is more dominant in the temporal coordination of performance ensembles: adapting to the changing tempo of one's partners or honoring musical roles that may determine who sets the tempo? Figure 1 demonstrates the cross-correlations between the interonset timing of two simultaneous parts when pianists play in solo performance (Figure 1a and 1b) or in duet performance (Figure 1c–1f). Figure 1e further displays the cross-correlations in the leader/follower instructions of Goebel and Palmer (2009), and Figure 1f displays the cross-correlations from the removal of auditory feedback to the leader about the follower's part. Lag 0 correlations indicate the degree to which interonset intervals in the upper musical part (melody) correspond to those in the lower part (accompaniment); a high value is seen in solo performance and a low (non-significant) value in duet performance, owing to the fact that it takes time for performers to note the tempo change of their partner. In Figures 1a–1d, Lag 1 correlations indicate that the lower part (accompaniment) tracked the upper part's timing at a delay of one tone, and Lag -1 correlations

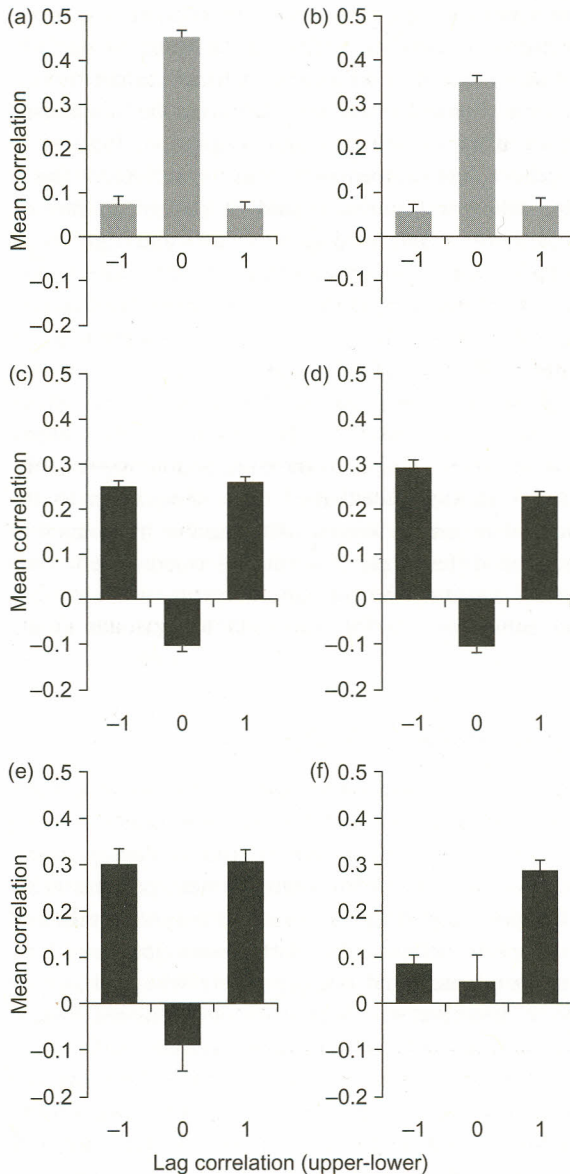


Figure 1 Mean cross-correlations among interonset intervals for the upper (melody) and lower (accompaniment) parts in performances of novel 2-part piano pieces. Each graph represents the data of 16 pianists. (a), Solo performance; (b), solo performance; (c), duet performance, with fixed partner; (d), duet performance, with changing partner; (e), duet performance, leader (upper)/follower (lower) roles; (f), duet performance, leader/follower roles with reduced auditory feedback to leader (see text for further description). Parts (a) and (c) based on data from Palmer and Loehr (2012), (b) and (d) based on data from Loehr and Palmer (2011), (e) and (f) based on data from Goebel and Palmer (2009).

indicate that the upper part tracked the lower part's timing at a delay of one tone. In Figures 1e and 1f, Lag 1 correlations indicate that the follower tracked the leader's timing at a delay of one tone, and Lag -1 correlations indicate that the leader tracked the follower's timing at a delay of one tone.

The adaptation patterns in duet performance are remarkably consistent across the different studies shown in Figure 1. The fact that cross-correlations at Lags 1 and -1 are large in Figure 1c, 1d, and 1e (normal duet performance) suggests that

both duettists are adapting to the other's timing, regardless of whether leader/follower roles are assigned. In addition, the pianists adapted to a range of partners (across the duet pairs; Figure 1c) as well as they adapted to a fixed partner (across duets; Figure 1d). Furthermore, biomechanical differences between the hands used (left versus right) do not appear to influence the temporal adaptation; Figures 1c and 1d (Loehr & Palmer, 2011) reflect duet performance with the left hand (lower part) and right hand (upper part), whereas Figures 1e and 1f (Goebl & Palmer, 2009) reflect duet performance with the right hand (lower part) and right hand (upper part), which yielded remarkably similar adaptation patterns. The only condition in which bidirectional adaptation is disrupted is when auditory feedback is reduced (Figure 1f) and the leader cannot hear the follower. The reduced Lag -1 correlation in this condition reflects the lack of adaptation of the leader to the follower's timing, who appears to be adapting to the leader (Lag 1) as much in reduced feedback (Figure 1f) as during full auditory feedback (Figure 1e). Despite the musical roles assigned, the leader always adapts to the temporal changes of the follower in the presence of normal auditory feedback. Thus, adaptation to the timing of one's partner in a musical ensemble seems to transcend influences of musical roles and any biomechanical differences; this finding is consistent with views that some aspects of temporal coordination (in particular, phase adaptation) are automatic, fast, and beyond conscious control (see also Konvalinka et al., 2010).

B. Individual Differences and Musical Roles in Ensembles

There are important individual differences in how musicians adapt to their partners in duet settings, in which each performer has a roughly equivalent opportunity to influence their fellow musician. Loehr and Palmer (2011) studied duet pianists' ability to perform right-hand melodies with the left-accompaniment performed by themselves or by their partner. Temporal coordination measures (asynchronies and cross-correlations of interonset intervals between the parts) were influenced by individual differences between partners' preferred rates; partners who had similar preferred rates in solo performance were better synchronized and showed mutual adaptation to each other's timing during duet performances. Neither performer's preferred rates correlated with the duet performance measures; it was the mismatch between the performer in each pair (relative differences) rather than the characteristics of either individual (absolute levels) that predicted the temporal characteristics of the joint performance. Pecenka and Keller (2011) likewise documented individual differences in amateur musicians' ability to synchronize in a duet tapping task. Individuals with high or low prediction tendencies (as measured in a nonmusical temporal task) tapped with a metronome in synchrony with another musician with similar or different prediction tendencies. Duets composed of two high-prediction individuals tapped with higher accuracy and less variability than low-prediction duettists, whereas mixed duets performed at an intermediate level. The authors reported that the match of prediction tendencies explained the duet synchronization performance beyond the explanatory power of differences in their

individual synchronization abilities; this emphasis on the role of relative (not absolute) relationships between individual performers in predicting their ensemble performance coordination is similar to the temporal predictions made by Loehr and Palmer (2011) in duet piano performance.

Ensemble jazz performance offers a particularly challenging case of temporal coordination. Jazz performers have certain stylistic freedom to wander away from an underlying beat. Friberg and Sundstrom (2002) analyzed the rhythmic properties of swing tendencies for ensemble performers to play on the beat, before the beat, or after the beat by analyzing jazz solos performed by drummers in jazz ensemble recordings. The timing of cymbal strokes indicated a linear decrease in the swing ratio, defined as the ratio formed by the relative durations of successive eighth notes, as the tempo increased; the ratio of long-short tones varied from 3:1 at slow tempi to 1:1 at faster tempi. The temporal coordination of the soloist (piano, saxophone, or trumpet) in each jazz ensemble relative to the drummer indicated that soloists performed after the cymbal on positions of metrical downbeats and that temporal disparity was larger at slower tempi. Interestingly, a different pattern emerged for offbeats; the soloist's tone onsets were more synchronous with the drummer's cymbal, and this synchrony yielded smaller variance. Thus, soloists tended to play around the drummer's beat and drummers played with a larger swing ratio (with values up to 4:1), despite the drummers' primary role of maintaining the beat. This example captures the fine temporal control necessary between ensemble performers, even (or especially) in a style that permits significant temporal variation within performers (Ashley, 2002; Schober & Levine, 2011).

Another arena in which sensorimotor cues influence ensemble performance is that of conducting. Conductors typically use both simple and complex gestures to direct an ensemble of musicians who play different musical parts on a variety of instruments. Luck and Toiviainen (2006) captured the movements of a conductor's gestures during a 20-min performance. One hypothesis tested was that the musicians would synchronize primarily with the auditory cues of their fellow performers, while following the visual cues of the conductor in a looser fashion. The timing of the conductor's baton motions was cross-correlated with the timing of the ensemble's performance, measured by the beat rate as specified in the audio signal. The performances were categorized on the basis of the clarity of the beat as communicated by the conductor. The ensemble's performance tended to be more synchronous with (higher cross-correlations and smaller lag between) the conductor's movements for pieces designated as having a clear beat. Thus, the real-world situation of ensemble performers who synchronize with a conductor while hearing other performers suggests that sensorimotor integration of one's own performance with one's acoustic/visual environment becomes more complex than simple models to date can capture.

Sociological factors influence motion cues in ensemble performance as well. Davidson and Good (2002) videotaped and coded string ensemble performers' movements for extramusical interpersonal dynamics such as the roles assumed by different members and comments about performance anxiety. In addition, comments about the coordination of the content were made, including tempo changes and style of attacks. These comments were compared with eye gaze by individual performers,

and the movement gestures (with arm gestures, bowing movements, and head movements) of exits and entrances of different parts that performers played. The authors reported a correlation between the performers' movement size (large arm or head movements) and the size of the sound change (loud or soft). Related findings were reported for pianists preparing duets (Williamon & Davidson, 2002); analyses of video recordings over several practice sessions indicated that the pianists increased their use of nonverbal gestures and eye contact during practice sessions to increase their coordination at locations in the music identified by pianists as important or difficult. Maduell and Wing (2007) studied nonverbal and social factors in a flamenco ensemble composed of a dancer, singer, clapper (palmera), and guitarist. Nonverbal cues for rhythmic control were observed for each performer; head and foot movements were most common, and the dancer as focal point of the group used the most rhythmic cues. The authors propose a network of control structures in which the focus, or relative importance of each ensemble performer's part, is determined mainly by musical factors and the status of each ensemble performer is determined mainly by social factors such as experience and knowledge. Although there is little measurement of ensemble motion reported to date, these findings are suggestive that the timing of nonverbal cues that arise from social as well as musical factors can be critical for successful ensemble performance.

A final consideration is how people learn to coordinate their movements with others, especially during childhood. The capacity to synchronize body movements with an external rhythm is fundamental to music, dance, and activities such as carrying heavy objects or walking together. A few studies have begun to examine how children learn to spontaneously synchronize their body movements to an external beat. Kirschner and Tomasello (2008) asked children 2–5 years old to drum along with a human partner, with a drumming machine, or with a drum sound from a speaker. When drumming with the experimenter, children as young as 2 years old displayed a smaller variance in their asynchronies with the underlying isochronous beat that was aligned with the experimenter's beat. Both nonsocial conditions (playing with a drumming machine or with a drum sound) yielded a larger variance in asynchronies. Because the social condition is the only one in which both visual and auditory cues were present, it is not clear whether improved synchronization was due specifically to the types of sensory information or to the social presence of the partner. Nonetheless, this study and more recent findings that joint music making by 4-year-olds led to increased spontaneous cooperative and helpful behavior, compared with a matched control condition that lacked joint music making (Kirschner & Tomasello, 2009), opens the door for several paradigms that address hypotheses of how people learn to coordinate with their fellow musicians.

IV. Summary

Novel methods of capturing empirical measurements of music performance have yielded additional insights into the online use of multiple sensory systems in a

variety of performance settings. Despite the wealth of data available from these methods, current theory of performance awaits an equivalent jump in theoretical power. Future lines of research that should prove fruitful include further studies with children who learn to perform together, as related to theories of action simulation, dynamical systems, and fundamental questions about the evolution of humans' coordination skills. Also important is the scaling up of computational theories of individual performance to group performance, an area that is already undergoing development, and the application of brain imaging techniques such as electroencephalography and transcranial magnetic stimulation to joint behaviors, a line of work that has just begun to develop fruitful techniques (see Chapter 14, this volume). In sum, this era is an excellent time to conduct research with performing musicians.

Acknowledgments

The research reported here was funded in part by NSERC Grant 298173, NSERC Accelerator Award, and a Canada Research Chair to the author. Thanks are due to Janeen Loehr for comments on an earlier draft of this chapter.

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