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Musical ensemble performance: A theoretical framework and empirical findings on interpersonal coordination

Peter E. Keller

The MARCS Institute, University of Western Sydney, Australia

Musical ensemble performance requires precise yet flexible interpersonal coordination. The former Max Planck Research Group on Music Cognition and Action investigated the psychological processes and brain mechanisms that enable such coordination. This paper provides an overview of the group's research on factors that determine the quality of ensemble cohesion. First, the theoretical framework and empirical approach that guided our work are outlined, and then key findings are described. These findings address the role of individual differences in cognitive-motor ensemble skills (anticipation, attention, and adaptation), social-psychological factors (personality), and the performer's knowledge about the music and familiarity with co-performers. The paper ends with a discussion of the implications of our research for pedagogical practice aimed at fostering excellence as an ensemble musician.

Keywords: ensemble; coordination; timing; skill; individual differences

Musical ensemble performance can be viewed as a pristine social art form that places exceptional demands upon the cognitive-motor capacities of co-performers. A particularly remarkable feature of ensemble performance is the exquisite balance that individuals are able to achieve between temporal precision and flexibility in interpersonal coordination. Such coordination is typically a highly creative affair involving diverse body parts, a variety of complementary roles played by different individuals, and adaptability to changing cognitive, motor, affective, and social demands that arise during performance. Yet competent co-performers are able to synchronize their actions with consistently high levels of accuracy. Investigating the psychological processes and neurophysiological mechanisms that enable a balance between precision and flexibility is essential to understanding human collaborative music making. The current paper provides a glimpse into the research conducted on this topic by members of the Max Planck Research Group on Music Cognition and Action, which was active at the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig, Germany, from 2007 until 2012. There are, of course, researchers elsewhere doing excellent work on ensemble performance, but that work is not reviewed here.

MAIN CONTRIBUTION

The broad aim of the Leipzig Music Cognition and Action (MCA) group was to investigate the behavioral and brain bases of human interaction in musical contexts. The research agenda pursued by the group was guided by a theoretical framework addressing how basic temporal coordination between co-performers is supported by a set of core cognitive-motor ensemble skills. This framework was explored using an empirical research strategy that focused on individual differences in ensemble skills. Our studies employed performers in diverse ensembles—piano duos, choral groups, jazz combos, and gamelan musicians—but our most rigorous research efforts were directed towards ensemble performance in the tradition of western classical chamber music.

The theoretical framework and research strategy were applied chiefly to three topics: (1) online cognitive-motor ensemble skills and their neural correlates, (2) knowledge about musical structure and stylistic expression, (3) social factors that influence ensemble coordination. In the current paper, I will give a brief description of the theoretical framework and the empirical research strategy before highlighting key results pertaining to these three topics.

Theoretical framework

The theoretical framework (Keller 2008) assumes that three core cognitive-motor skills determine the quality of real-time interpersonal coordination during musical ensemble performance. The first skill relates to anticipatory mechanisms, such as mental imagery, that are involved in planning a performer's own actions and predicting other ensemble members' actions. The second skill concerns the process of dividing attention between one's own actions and those of others while monitoring the overall, integrated ensemble output. The third ensemble skill is based upon adaptive mechanisms that allow performers to react to variations in each other's action timing and other performance parameters (e.g. intensity). The original framework has recently been extended (Keller in press) to address how the three skills interact with one another, as well as with social-psychological factors (e.g. variables related

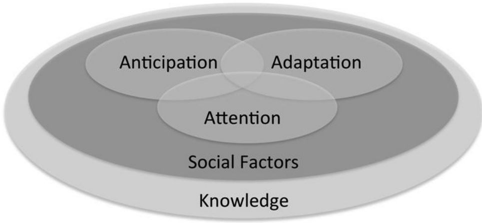

Figure 1. Theoretical framework for musical ensemble performance.

to personality) and the performer's knowledge about the music and familiarity with co-performers (see Figure 1).

Empirical approach

The empirical approach adopted by the Leipzig MCA group capitalized upon differences in the quality of ensemble coordination that can be observed even among groups of the most assiduously trained musicians. We used this inter-individual variation to gain purchase on the psychological and neurophysiological bases of musical ensemble performance. The fundamental assumption behind our approach is that an individual's ability to coordinate with co-performers in an ensemble is, in large part, determined by his or her abilities related to the three cognitive-motor ensemble skills (anticipation, attention, and adaptation). Based on this assumption, our research program was organized around a set of three empirical goals.

Our first empirical goal was to examine the three ensemble skills using both qualitative and quantitative methods. The qualitative procedures included interviews with internationally renowned ensemble performers (e.g. the Labèque sisters and members of the Chicago Symphony Orchestra; see Keller in press). Our quantitative procedures consisted of a battery of perceptual and motor tasks that yield objective behavioral measures of an individual's anticipation, attention, and adaptation abilities. The functional processes behind these behavioral measures were interrogated through computational modeling and computer simulations, while the brain structures and neurophysiological mechanisms that support these functions were investigated using neuroimaging and brain stimulation techniques.

The group's second empirical goal was to address relationships between individual differences in the three ensemble skills and performance on naturalistic interpersonal coordination tasks. The naturalistic tasks that we employed included real musical ensemble performance (e.g. piano duos) and rudimentary forms of dyadic sensorimotor synchronization (joint finger-tapping). In our studies of ensemble performance, interpersonal coordination was measured at the level of sounds (i.e. audio or digital signals from electronic instruments) and body movements (recorded with motion capture systems). The relationship between ensemble skills and naturalistic task performance was investigated using two strategies. One strategy was correlational: it involved measuring interpersonal coordination under naturalistic conditions and assessing the cognitive-motor ensemble skills within a common sample of individuals, and then calculating the degree to which the interpersonal coordination could be predicted based on ensemble skill estimates. For example, a pilot study (Keller 2008) of a small sample of 14 pianists revealed that the three core cognitive-motor skills, in combination, accounted for over 90% of the variance in the quality of interpersonal coordination when the pianists played in duos. The second strategy entailed assessing ensemble skills, and then testing interpersonal coordination after assigning individuals to pairs based on their level on a given skill (e.g. low skill pairs vs. high skill pairs vs. mixed pairs).

Finally, our third empirical goal targeted factors that potentially mediate the relationship between cognitive-motor ensemble skills and naturalistic interpersonal coordination. Two broad classes of factor were of interest: knowledge representations and social factors. Our methods for addressing the role of knowledge representations included manipulating the degree to which co-performers were familiar with each other's part in ensemble coordination tasks. The impact of social factors was explored by using psychometric instruments to assess social-cognitive variables (e.g. empathy).

Key findings: A selection

In the following, I describe key findings that emerged from the MCA group's empirical research on topics related to musical ensemble performance. I begin by reviewing selected results of our research on cognitive-motor ensemble skills before presenting some work on co-performer knowledge and social factors.

Ensemble skills

Ensemble performers in the western classical tradition (and indeed many other traditions) invest considerable time into collaborative rehearsal in order to establish shared performance goals, i.e. unified conceptions of the ideal integrated ensemble sound. Shared performance goals ensure that expressive variations in performance parameters—including timing, intensity, articulation, and intonation—are aligned across musicians. Once shared goals are consolidated, the challenge is to realize them faithfully during performance under the real-time demands and vagaries of live musical interaction. The research described in this section of the present paper is concerned with the cognitive-motor ensemble skills that assist co-performers to meet this challenge by allowing them to anticipate, attend, and adapt to each other's actions in the heat of the moment. I will limit the discussion to temporal aspects of interpersonal coordination, setting aside other expressive parameters (see Keller in press) or affective dimensions associated with joint music making (see Phillips-Silver and Keller 2012).

Anticipation. Anticipatory cognitive-motor mechanisms operate in an online manner (during performance) to enable ensemble musicians to plan the production of their own sounds and to generate predictions about the upcoming sounds of co-performers. The MCA group's research into anticipatory mechanisms focused upon the role of covert action simulation in such online prediction. A study that served as a precursor to this work was conducted together with Guenther Knoblich and Bruno Repp (Keller *et al.* 2007). In this study, pianists were asked to record one part from several duets and then, a few months later, to play the complementary part in synchrony with either their own or others' recordings. Synchronization was most precise when the pianists played with their own recordings. We argued that this was the case because pianists predicted the timing of sounds in the recordings by engaging in online simulation of the performances. According to this account, such simulation led to a self-synchronization advantage because the match between simulated event timing and actual timing in a complementary part is best when both are products of the same cognitive-motor system.

At the time when we did this preliminary work on the role of action simulation in predicting others' actions, I was also conducting research on the role of mental imagery in musical action planning (Keller and Koch 2006, 2008, Keller, Dalla Bella, and Koch 2010). The confluence of these lines of research led to the proposal that predictions based on action simulation are experienced as mental images for upcoming sounds and movements (Keller 2008, 2012). This spawned a number of studies that investigated the relationship between mental imagery, temporal prediction, and interpersonal coordination. The first, a study of piano duos (Keller and Appel 2010), found that interpersonal keystroke synchrony (measured with digital pianos) and body sway coordination (measured with a motion capture system) were positively correlated with performance on a separate task designed to measure the vividness of anticipatory auditory imagery in each pianist.

This theme was taken up by Nadine Pecenka, a doctoral student in the MCA group. Her first study (Pecenka and Keller 2009) provided evidence that auditory imagery facilitates synchronization due to its role in temporal prediction. Auditory imagery ability was assessed using a perceptual judgment task that required participants to mentally continue a tempo change in a short auditory sequence with a gap, and then to judge whether a probe tone occurred early or late relative to the imagined continuation. Prediction tendencies were indexed by a task that required finger tapping with auditory pacing signals that contained tempo changes: Prediction was assumed to be high to the extent that inter-tap intervals matched (rather than lagged behind) pacing signal inter-onset intervals. Positive correlations were found between auditory imagery ability, prediction tendencies, and accuracy on various sensorimotor synchronization tasks. A subsequent study (Pecenka and Keller 2011) showed that these relations have implications for interpersonal coordination. Individuals with high or low prediction tendencies were required to tap (with percussion sounds as auditory feedback) in synchrony with an individual who displayed similar or different tendencies. The results indicated that paired participants' individual temporal prediction abilities accounted for 30% of the variance in the precision of dyadic sensorimotor synchronization.

What are the brain mechanisms that underlie predictions generated via action simulation? Our theoretical framework assumes that the process of action simulation is driven by two types of "internal model" that represent sensorimotor associations between motor commands that issue from the brain and the sensory experience of events in the immediate environment (Keller 2008, 2012). "Forward models" represent links between motor commands (e.g. to lower a finger) and their effects on the body and environment (the tactile sensation of striking a piano key and the auditory sensation of hearing a tone). "Inverse models" represent transformations from intended action outcomes (tones) to the motor commands that produce them. A recent brain imaging study using functional Magnetic Resonance Imaging (fMRI) revealed that temporal prediction during sensorimotor synchronization is supported by a distributed network of cortical areas (including prefrontal cortex, premotor cortex, superior/middle temporal gyrus, and sensorimotor cortex) that may commune with internal models in the cerebellum (a corrugated structure at the lower backend of the brain) (Pecenka *et al.* in press).

Importantly, our framework assumes that separate classes of forward and inverse models are harnessed to simulate one's own and others' actions slightly in advance of their production (Keller 2008). The coupling of "own" and "other" internal models facilitates fluent interpersonal coordination by allowing potential errors in timing to be anticipated and corrected before they occur (van der Steen and Keller 2013). Evidence for two classes of internal model comes from a transcranial magnetic stimulation (TMS) study run by Giacomo Novembre, a doctoral student in the group (Novembre *et al.* 2012). TMS is a brain stimulation technique that, when coupled with electromyography, can be used to assess the excitability of an individual's motor system. The aim of our study was to investigate how the ensemble musician's brain engages in the simulation of actions associated with the self or another performer. Pianists performed the right-hand part of piano pieces, previously learned bimanually, while the complementary left-hand part was either not executed or (believed to be) performed by a co-performer (an experimenter feigned playing while the participant actually heard a recording). Results indicated a clear self-other distinction in action simulation: Excitability of the motor system was facilitated when simulating the other performer but inhibited when simulating the self. A subsequent study found that using repetitive TMS to disrupt neural activity in brain regions implicated in action simulation interfered with pianists' ability to adapt to tempo changes in recordings, but only when the pianists had themselves practiced the recorded parts beforehand and were hence more likely to simulate them (Novembre *et al.* in press).

Attention. Ensemble performance involves concurrently paying attention to one's own actions (high priority) and those of others (lower priority) while monitoring the overall ensemble sound. This form of divided attention, which has been termed "prioritized integrative attending" (Keller 2001), is demanding to the extent that it requires the simultaneous segregation and integration of information from separate auditory streams. It has been proposed that the flexibility required to attend to multiple levels of musical texture is enabled by metric frameworks—hierarchical temporal schema that are yoked to the music's metric structure (Keller 1999, 2008). The dynamics of prioritized integrative attending have been studied using dual-task paradigms that require musicians to memorize or produce one instrumental part while simultaneously memorizing another part or the aggregate structure of multipart rhythm patterns (Keller and Burnham 2005). These dual tasks were designed to capture the demands of music characterized by complex interlocking rhythms, as in Central African music and Balinese gamelan, and work in our group demonstrated that individuals with experience performing such music display relatively good prioritized integrative attending skills (Keller and Schroeder 2010). Recently, an fMRI study conducted by doctoral student Marie Ragert (née Uhlig) identified a fronto-parietal brain network that is involved in regulating the balance between the process of segregating a high-priority part and the process of integrating parts during prioritized integrative attending (Uhlig *et al.* 2013).

Adaptation. Adaptive mechanisms control adjustments to the timing of ensemble members' actions so that they maintain synchrony in the face of small random irregularities and expressively motivated deviations in local tempo, as well as larger tempo changes and errors disrupting rhythm. Research in the MCA group focused on two forms of mutual temporal adaptation: assimilative and compensatory (see Nowicki *et al.* 2013). Assimilative adaptive timing involves co-performers automatically copying small fluctuations in the timing of each other's actions. Such mutual temporal assimilation may be a form of non-conscious behavioral mimicry that facilitates ensemble cohesion by making multiple individuals sound collectively as one. Compensatory adaptive timing is driven by error correction mechanisms that enable internal timekeepers—instantiated as oscillations of neural populations in co-performers' brains—to remain entrained (coupled to one another) under conditions where timing is variable.

Two separate mechanisms are assumed to subserve temporal error correction. Phase correction is an automatic process that adjusts the way in which the sequence of pulses generated by an internal timekeeper in one performer is aligned against a sequence of pulses generated by a timekeeper in a co-performer. Period correction involves consciously controlled adjustments to the duration of timekeeper intervals, and is invoked when a performer intentionally adapts to tempo changes produced by a co-performer. While phase correction reduces the variability of asynchronies, thus supporting precision in basic temporal coordination, period correction allows the flexibility that is required for co-performers to accommodate expressively motivated tempo changes.

The degree to which an individual engages in error correction can be estimated by analyzing the time series of asynchronies between finger taps and pacing events in sensorimotor synchronization tasks (e.g. Repp *et al.* 2012). An early study conducted with Bruno Repp showed that a secondary task (mental arithmetic) reduced period correction but not phase correction during synchronization with tempo changes, suggesting that only period correction requires attentional resources (Repp and Keller 2004). However, error correction estimates obtained in experiments employing computer controlled virtual synchronization partners that are programmed to vary in cooperativity (i.e. amount of error correction) have revealed that, while human phase correction remains constant across a range of cooperative virtual partners, its gain can be increased when confronted with uncooperative partners (Repp and Keller 2008). The distinction between automatic and effortful forms of adaptive timing is supported by brain imaging work on sensorimotor synchronization with virtual partners. An fMRI study conducted together with

Merle Fairhurst and Petr Janata found that small shifts in the degree of adaptive timing employed by virtual partners led to large-scale switches in the brain networks activated in participants due to changes in the need for cognitive control (Fairhurst *et al.* in press).

The implications of individual differences in adaptive timing for real interpersonal coordination were borne out in a study of dyadic sensorimotor synchronization (Keller *et al.* 2012). Phase correction was estimated in a sample of individuals who were subsequently paired to form "high-correcting" dyads and "low-correcting" dyads. Each dyad performed a synchronization-continuation task that required both individuals to tap together (with auditory feedback) in time with an auditory pacing sequence and then to continue tapping together when the sequence stopped. Results suggested that, while coordination was generally stable in high-correcting dyads, low-correcting dyads needed to increase the degree of error correction that they employed in order to stabilize their performance during continuation tapping. Such increases are most likely effortful and may have costs in the attentionally demanding arena of musical ensemble performance (e.g. the control of expressive performance parameters may be compromised).

Knowledge

Shared performance goals established during joint rehearsal contain information about musical structure and the expressive intentions and playing styles of ensemble members. Ensemble cohesion is thus constrained to some degree by each performer's knowledge about the structure of co-performers' parts and their stylistic tendencies. A study by Marie Ragert suggests that these two varieties of knowledge—structural and personal—serve different functions and can have dissociable effects on ensemble coordination.

In our study (Ragert *et al.* 2013), pairs of unacquainted pianists came to the lab after practicing either one part or both parts of several piano duets at home. The complementary parts of the duets were therefore familiar in one condition and unfamiliar in the other. Pianists' keystroke timing was recorded on digital pianos and their body movements were tracked with a motion capture system as they played repeat performances across six takes in each condition. Results pointed to a partial dissociation between interpersonal coordination at the level of keystrokes and body sway. Variability in keystroke asynchronies decreased across the takes, and was generally lower in the unfamiliar condition than the familiar condition. This indicates that coordination started out better, and remained so, when pianists had not rehearsed their co-performer's part. By contrast, body sway coordination (quantified by estimating “mutual information”) was high throughout the takes in the familiar condition, while it started out low and improved across takes in the unfamiliar condition.

These findings suggest that knowledge affects interpersonal coordination by influencing predictions at different timescales. Familiarity with a co-performer’s part, but not their playing style, engenders predictions about expressive micro-timing variations that are based instead upon one’s own personal playing style, leading to a mismatch between predictions and actual events at short timescales. As knowledge about a co-performer’s stylistic idiosyncrasies is acquired, however, the individual learns—through the calibration of internal models—to simulate the other’s action style. Familiarity with the structure of a co-performer’s part, on the other hand, facilitates predictions at longer timescales related to high-level metric units and musical phrases, and reflected in ancillary body sway movements.

Social-psychological factors

Musical ensemble performance is a social activity to the extent that it involves cooperation and the communication of aesthetic ideas between individuals. The research program of the Leipzig MCA group was concerned with social-psychological factors that potentially affect the dynamics of interpersonal coordination by influencing the core cognitive-motor ensemble skills.

One study (Fairhurst *et al.* 2013) addressed the relationship between temporal adaptation, leader-follower tendencies, and locus of control—an aspect of personality related to the degree to which life events are perceived to be a consequence of one’s own actions. The aim of the study was to identify behavioral strategies and patterns of brain activity that distinguish between individuals with different leader-follower dispositions when they interact with synchronization partners with high or low levels of competence. This was examined in an fMRI experiment that required individuals to synchronize finger taps with sounds produced by virtual partners who varied in terms of competence at maintaining a steady tempo. For performance to be successful, the human participant must assume responsibility for maintaining the tempo when the virtual partner cannot. Results indicated that “leaders” (individuals who attribute the cause of events to their own actions) generally engaged in less adaptive timing than “followers” (who attribute events to external factors). This may reflect a difference in strategy: while followers prioritized the task of synchronizing with their partner (at the expense of maintaining a steady tempo), leaders focused on stabilizing the tempo of their own performance (at the expense of synchrony when the partner was low in competence). Brain regions implicated in evaluating agency (e.g. the precuneus) were activated more strongly in leaders than followers, suggesting greater self-focus in leaders.

Another aspect of personality that may impact upon self-other relations during interpersonal coordination is empathy. Our studies on this topic have identified links between empathy—which is a matter of understanding others' thoughts and feelings—and anticipatory mechanisms related to action simulation. One of the TMS studies described earlier (Novembre *et al.* 2012) found a positive correlation between the degree to which one pianist represented the other's part in their own motor system (as indexed by its excitability) and scores on an empathy questionnaire subscale assessing the tendency to adopt others' perspectives. Furthermore, the degree to which repetitive TMS interfered with tempo adaptation in our follow-up study (Novembre *et al.* in press) was also positively correlated with perspective-taking tendencies. Finally, it was found that perspective-taking is correlated with the degree to which individuals predict event timing during sensorimotor synchronization with tempo-changing pacing sequences (Pecenka and Keller 2011).

IMPLICATIONS

The mission of the Leipzig MCA group was to shed light on the psychological processes and brain mechanisms that support precise yet flexible interpersonal coordination in musical contexts. Although the group's research was not geared towards specific applications, some of our findings could potentially inform pedagogical practice aimed at fostering excellence as an ensemble musician. Here I discuss four relevant implications.

An obvious implication of our research is that the enormous amount of experience that is necessary to attain mastery in solo performance needs to be supplemented by a complementary regimen of specialized training dedicated to the development of strategies and skills for ensemble performance. We have identified a suite of cognitive-motor skills that facilitate ensemble cohesion by allowing performers to anticipate, attend, and adapt to the actions of co-performers in real-time. Our results support the hypothesis that individual differences in these cognitive-motor skills constrain the ability of ensemble members to coordinate with one another. It would therefore be beneficial to design techniques for exercising these skills in order to boost each individual's capacity for precise yet flexible ensemble coordination.

A second implication of our work is related to the fact that interpersonal coordination in ensembles takes place at multiple levels that evolve at different timescales. Sounds triggered by instrumental movements communicate information about expressive micro timing, while ancillary movements such as body sway communicate expressive information on longer timescales at which musical phrases and higher-order structural units are defined. Our research suggests that interpersonal coordination at these multiple levels relies upon different types of knowledge, with coordination at long timescales benefitting from familiarity with the structure of co-performers' parts, and coordination at short timescales benefitting from familiarity with co-performers' playing styles. It follows that optimal collaborative rehearsal strategies should deliberately encourage the acquisition of both types of knowledge. An additional type of knowledge—one that characterizes partnerships that span decades (e.g. the Labèque sisters)—concerns familiarity with a co-performer's cognitive-motor ensemble skills, that is, how he or she anticipates, attends, and adapts to others. Such knowledge can be considered to be a meta-ensemble skill that allows performers to apply adaptive mechanisms on the basis of anticipated relations between their own and others' actions (van der Steen and Keller 2013).

A third implication of our work is that the impact of social-psychological factors extends beyond influencing the effectiveness of co-performer communication during rehearsal, to affecting the operation of cognitive-motor ensemble skills during performance. Our studies revealed links between empathy and anticipation skills, on one hand, and locus of control and temporal adaptation, on the other. These findings highlight the importance of taking factors such as personality into account when techniques for developing ensemble skills are tailored to individuals. Some young musicians may have personalities that favor the spontaneous development of a complete kit of cognitive-motor ensemble skills, while other individuals may need to invest special effort into training particular skills. Indeed, links between personality and the three skills may predispose individuals towards playing certain roles in ensembles (e.g. soloist versus accompanist; independent versus doubled voice).

Finally, our research findings invite comment on the issue of whether the match between co-performers in terms of their idiosyncratic stylistic tendencies—which may vary as a function of personality and biomechanical factors related to anthropometric characteristics (see Keller in press)—is an important determinant of the quality of ensemble cohesion. Our studies of the self-synchronization advantage and dyadic sensorimotor synchronization suggest that it is not necessarily the match in playing style per se that leads to good coordination, but rather the fact that stylistic similarity allows each performer to anticipate, attend, and adapt to the other's actions effectively. This implies that highly refined ensemble skills may enable co-performers to transcend their individual musical identities to achieve a group identity, and, with it, a form of expression that arises uniquely through interpersonal coordination in musical contexts.

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Address for correspondence

Peter E. Keller, The MARCS Institute, University of Western Sydney, Locked Bag 1797, Penrith, New South Wales 2751, Australia; *Email:* p.keller@uws.edu.au

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