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14 Joint Action in Music Performance

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Abstract. Ensemble musicians coordinate their actions with remarkable precision. The ensemble cohesion that results is predicated upon group members sharing a common goal; a unified concept of the ideal sound. The current chapter reviews research addressing three cognitive processes that enable individuals to realize such shared goals while engaged in musical joint action. The first process is auditory imagery; specifically, anticipating one's own sounds and the sounds produced by other performers. The second process, prioritized integrative attention, involves dividing attention between one's own actions (high priority) and those of others (lower priority) while monitoring the overall, integrated ensemble sound. The third process relates to adaptive timing, i.e., adjusting the timing of one's movements in order to maintain synchrony in the face of tempo changes and other, often unpredictable, events. The way in which these processes interact to determine ensemble coordination is discussed.

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14.1 Introduction

In musical contexts within all known cultures and most echelons of society therein, temporally precise inter-individual synchronization can be observed among instrumentalists and dancers, and between performers and audience members. This type of synchrony is unique to humans, not by virtue of its precision − chorusing crickets and frogs are masterfully coordinated [1] − but rather due to the flexibility with which it is rendered. Human synchronization is a creative affair. It can be achieved through the use of different effectors (such as hands, feet, hips, shoulders, and heads), it can result in a seemingly infinite number of temporal structures (by coordinating rhythms with varying levels of complexity), and it is characterized by rapid adaptation to tempo changes in familiar and unfamiliar musical styles (for example, when dancing to the music of a foreign culture). Nowadays people even engage in musical synchronization via the Internet [2].

The current chapter is concerned with the cognitive processes that enable humans to coordinate their actions with the remarkable precision and flexibility that can be observed during musical joint action, i.e., musical activity involving more than one participant. Although these processes are most likely recruited to some degree regardless of whether the activity is clearly overt such as in instrumental performance and dancing, or more covert such as in listening, the focus here will be on music performance by trained individuals.

In musical ensembles, performers engage in mutually coupled, affective exchanges that are mediated by instrumental sounds and expressive body gestures. Ideally, the entrainment underlying such activity should not only result in the coordination of sounds and movements, but also of mental states. Thus, in accordance with enactive approaches to social cognition [3], performers intentionally and actively participate in making sense of the music so that its ‘meaning’ is shared among co-performers and communicated to audience members. This interactive form of enaction requires each performer to be sensitive to the subjective states expressed by his or her co-performers. Musical joint action therefore exercises the human predisposition for intersubjectivity [4] on grounds where meaning is essentially ineffable, highly embodied, and usually ‘make-believe’ (in the sense that a musician does not need to be sad to play mournfully).

Consider a pair of pianists playing a duet. How do they coordinate their actions with sufficient precision to produce complex sound patterns that − far from being mechanically regular − are exquisitely and purposefully structured in time? The ability to synchronize in this way obviously relies upon considerations apart from the technical command of one’s instrument. To produce a cohesive ensemble sound, the pianists must hold a common goal; a shared representation of the ideal sound. This chapter begins by discussing ensemble cohesion and shared musical goals, and then goes on to describe research addressing three specific ensemble skills that are assumed to enable performers to achieve such goals. These core ensemble skills, which are rooted in cognitive processes that most likely facilitate joint action more generally [5, 6], are anticipatory auditory imagery, prioritized integrative attention (a form of divided attention), and adaptive timing. The chapter ends by considering how these ensemble skills interact to determine the quality of ensemble cohesion during musical joint action. New data from a piano duet study will be introduced for illustrative purposes at this later stage.

14.2 Ensemble cohesion & shared goals

Ensemble musicians usually aim to interact in a manner that is conducive to producing a coherent musical entity. The term ‘ensemble cohesion’ refers to how well separate instrumental parts gel together to form such an auditory Gestalt. Ensemble cohesion is predicated upon the musicians sharing a common performance goal, that is, a unified conception of the ideal sound. The formation of shared musical goals may be grounded in the automatic tendency for people engaged in joint action to develop mental representations of each others’ tasks [6]. However, it is assumed here that additional effort is required in the case of musical joint action.

The richness and specificity of performance goals vary as a function of the musical context (e.g., goals are more highly resolved − and consequently have less degrees of freedom − in scripted music than in improvised music [7]). Highly specific performance goals, which are the norm in Western art music, are established while preparing a musical piece for performance through both individual private practice (a mixture of playing one's instrument, listening to recordings, and studying musical scores) and collaborative rehearsal with other group members. During collaborative rehearsal, the formation of performance goals is governed by a mixture of social, conventional, and pragmatic considerations [8-11]. For example, factors such as personality can influence communication among group members, social stereotypes can determine how the opinions of various instrumentalists are weighted (soloists or those playing 'melodic' instruments often seem to have the last word), and the size of the group can determine how leadership is distributed among ensemble members − ranging from egalitarian piano duos, through democratic mixed chamber groups, to autocratic regimes where a conductor is expected to impregnate an entire orchestra with his or her performance goal.

In any case, once performance goals are established, they reside in memory as idealized mental representations of the sounds constituting the musical piece. Performance goals embody a performer's intentions and expectations about how his or her own sound *and the overall ensemble sound* should be shaped dynamically over time. With such goals in mind, musicians develop performance plans (usually during private practice) that guide the motor processes involved in translating the goal representations into appropriate body movements [12-15].

It seems reasonable to assume that ensemble cohesion will vary according to how well performance goals related to the overall sound are matched across ensemble members. Factors that may compromise the quality of this match include difficulties associated with memorizing the details of complex musical textures, and biases that result from individual differences in stylistic preference and the fact that each musician envisages the overall sound from the unique perspective of his or her individual performance plan. Importantly, though, the degree to which goal representations are shared is not the only determinant of ensemble cohesion. Performance goals must be realized (via the execution of performance plans) under the real-time demands and vagaries of live musical interaction. Three ensemble skills that are purported to enable performers to accomplish this—anticipatory auditory imagery, prioritized integrative attention, and adaptive timing—are considered next in turn.

14.3 Anticipatory auditory imagery

Ensemble performance requires each musician to anticipate his or her sounds and the sounds produced by other musicians. It is assumed here that these forms of anticipation involve mixtures of auditory and motor imagery, and that such top-down anticipatory processes coevolve with bottom-up expectancies generated on the basis of the perception of actual sounds (see [16, 17]). It is through the generation of auditory and motor images that musicians activate internal representations of performance goals and plans. While engaged in such imagery, the auditory component is most likely paramount in the performer's phenomenology: It is what an individual has in mind while playing. Indeed, accomplished musicians often express the opinion that greater performance excellence can be attained by imagining the ideal sound than by concentrating on motor aspects of performance (once the requisite technical skills have been acquired, of course) [18]. This notion sits comfortably with the ideo-motor approach to voluntary action. The central tenet of the ideo-motor approach is that actions are triggered automatically by the anticipation of their intended distal effects [19, 20]. As William James pointed out, a singer needs to think "only of the perfect sound" in order to produce it ([19] p. 774).

Anticipatory auditory imagery can facilitate the accurate performance of one's own part in at least three ways. First, such imagery may prime appropriate movements via functional links between auditory and motor brain regions that have developed through experience playing a musical instrument [21-24]. Second, auditory imagery may assist performers in meeting precise temporal goals, such as a steady tempo, by stabilizing motor control processes [25, 26]. Third, anticipatory auditory imagery may facilitate rapid performance by enabling thorough action preplanning. The degree to which performers engage in anticipatory auditory imagery during such planning increases with increasing musical experience [27]. Thus, although James' singer needed only to think of the ideal sound in order to produce it, he probably required a considerable amount of practice before being able to conjure such thoughts accurately and reliably. In case excessive private practice has made James' singer lonely, let us place him in a choir.

For James' singer to coordinate with his fellow choristers, it is necessary for him to predict what they will do, and, even more crucially, exactly when and how they will do it. The typical degree of asynchrony in musical ensembles (around 30-50 ms [28, 29]) is far smaller than would be expected if musicians were sheepishly reacting to the sounds of an individual serving as the leader. Instead, ensemble musicians make predictions about events in other parts by using auditory imagery to simulate the ongoing productions of their co-performers. This process was investigated recently in a study of piano duet performance [30]. Expert pianists were required to record one part from several unfamiliar piano duets, and then to play the complementary part in time with either their own or others' recordings after a delay of several months. It was assumed that pianists would be able to simulate upcoming events best in their own recordings because in this case the simulation is being carried out by the same cognitive/motor system − with all its idiosyncratic constraints − that generated the events in the first place. This was indeed the case: Pianists were more accurate at synchronizing with their own recordings than with others' recordings.

The task of coordinating the anticipatory auditory images required to guide one's own actions and simultaneously predict the outcomes of others' actions may be accomplished by multiple, tightly coupled *internal models* instantiated in the central nervous system. A distinction has been drawn between 'forward' and 'inverse' internal models in the field of movement neuroscience [31]. Both types of model are capable of learning to represent transformations between motor commands and sensory events based on experience with specific sensorimotor contingencies (e.g., the command to lower a finger in a particular manner, feeling the finger move against a piano key, and hearing a tone with particular qualities). The cerebellum has been identified as a likely seat of such learning [32]. The difference between forward and inverse models lies in the direction of the sensorimotor transformation.

Forward models represent the causal relationship between efferent motor signals − which issue from the supplementary motor area (SMA) to the primary motor cortex − and their ultimate effects on the body and the environment. Forward models have been ascribed roles in controlling one's own actions and in perceiving and understanding the actions of others. When used to guide one's own actions, forward models facilitate the efficiency of motor control processes by allowing movement errors to be corrected on the basis of predicted sensory feedback prior to the arrival of actual feedback [31]. In the context of action observation, it has been claimed that forward models allow the observer to simulate another individual's behavior and thereby predict its future course [33, 34]. Forward models may recruit the so-called 'mirror system' to some degree in doing so. On the basis of findings that similar premotor cortical activation patterns arise when an individual carries out an action and when the individual sees and/or hears somebody else performing the action, the frontal-parietal mirror system has been heralded as a key brain network mediating social interaction [35-38]. It has recently been shown that the mirror system resonates most strongly with actions that belong to the observer's own behavioral repertoire while listening to music or viewing dance [39-41].

Musical joint action may capitalize on both of the above functions of forward models. On this view, forward models representing one's own performance promote stable motor control by allowing movement errors to be corrected on the basis of anticipated auditory feedback while forward models representing the actions of one's co-performer(s) assist in predicting the 'what, when, and how' of upcoming auditory synchronization targets. The main difference between these two proposed classes of forward model lies in the nature of the efferent motor signals and tactile and proprioceptive feedback that they represent. Forward models of one's own performance presumably represent information about the specific movements associated with manipulating a particular musical instrument, whereas forward models of others' performances do not necessarily represent such specific movement-related information. Indeed, musicians in mixed ensembles readily synchronize with instruments that they cannot themselves play (which may have implications for the nature of the mirror system's involvement in musical joint action). Hence, the movement-related information represented by forward models of others' musical performances may be limited to relatively general, instrument-independent forms of body motion (e.g., swaying, rocking, and expressive gesturing) as well as vocal and articulatory activity that could potentially approximate others' sounds. Consistent with this notion, Ricarda Schubotz [42] has proposed that forward models run rudimentary simulations based on partial sensorimotor information when an observer is not capable of producing a perceived event sequence, and, moreover, vocal and articulatory loops in the lateral premotor cortex are engaged when predicting upcoming events in sequences whose structural properties are represented best in terms of musical parameters such as rhythm and pitch.

Inverse models sit opposite forward models. Traditionally, they represent sensorimotor transformations from desired action outcomes to the motor commands that give rise to these outcomes [32]. When playing music, the process of activating performance goal representations via auditory imagery can be considered to be akin to running inverse models.

It is assumed here that − as with forward models − musical joint action recruits two classes of inverse model, one dealing with the performance of one’s own part, and the other dealing with particular parts played by co-performers or the whole ensemble texture (depending on structural aspects of, and familiarity with, the music). The main distinction between these two classes is that inverse models representing one’s own part are associated with rehearsed performance plans endowed with the power to trigger instrument-specific motor commands, whereas inverse models representing other instrumental parts (or whole textures) are impotent in this regard. Although the generation of auditory images is mediated in both cases by a motor-related brain network incorporating the SMA and premotor cortex (in conjunction with the secondary auditory cortex) [43-45], appropriate motor commands for action are transmitted from the SMA to the primary motor cortex only on the basis of information from inverse models related to one’s own part. Nevertheless, inverse models representing others’ parts are not superfluous because without them the intended relation between parts—which musicians invest much time in learning—would be lost. Indeed, the correct performance of one’s own part is usually defined in terms of the relation between one’s part and other parts, as, for example, when the pianist assigned to the ‘secondo’ part in a duo may be required to play less loudly than the pianist playing the ‘primo’ part. In this case, the inverse model for the secondo pianist’s own part requires access to an inverse model representing the primo part in order to suggest motor commands that result in less forceful movements (hence softer sounds) than those being executed by the primo pianist.

Pairing inverse models of others’ performances with corresponding forward models would facilitate efficient motor control by allowing corrections to be made on the basis of the anticipated relation between parts rather than in response to the perception of actual discrepancies between one’s own and others’ actions. Such paired internal models are featured in MOSAIC-based models of social interaction [46], where ‘other’ inverse models provide input to ‘other’ forward models, and thereby influence predictions about upcoming likely states in one’s co-actors. Paired forward-inverse models of others’ parts would also be useful in the context of music because they would allow one performer to imagine another’s style of playing in his or her absence, as is presumably done during private practice geared towards preparing for an ensemble performance.

Thus, paired forward and inverse models that support motor learning and control in the context of one’s own actions may, in the case of musical joint action, be coupled with a second class of paired forward-inverse models specializing in anticipating others’ sounds. To function properly during musical joint action, the entire system of internal models would naturally need to be kept in tune with changes in the auditory scene via actual sensory feedback. The availability of such feedback is modulated by attention.

14.4 Prioritized integrative attention

There is usually a lot to contend with during musical joint action. In ensembles, individual musicians are not only responsible for producing their own parts correctly, but they must also maintain awareness of the relationship between their parts and parts played by others. It has been argued that prioritized integrative attention is the optimal strategy to meet such multiple-task demands [47, 48]. Prioritized integrative attention involves dividing attention between one's own actions (high priority) and those of others (lower priority) while monitoring the overall ensemble sound. This attentional strategy is assumed to facilitate ensemble cohesion by allowing musicians to adjust their performances based on the online comparison of mental representations of the ideal sound (i.e., the performance goal) and incoming perceptual information about the actual sound. Prioritized integrative attention is related to the social cognitive concept of 'joint attention' [49] to the extent that multiple performers attend consensually to the overall ensemble sound or to a common subset of sounds (such as when musicians playing accompanimental roles pay attention to a soloist).

A confluence of Mari Riess Jones' dynamic attending theory [50, 51] and ideas related to Daniel Kahneman's [52] conception of fluctuations in autonomic arousal has led to the proposal that *metric frameworks* may drive prioritized integrative attention during musical joint action [48]. Metric frameworks are cognitive/motor schemas that comprise hierarchically arranged levels of pulsation, with pulses at the 'beat level' nested within those at the 'bar level' in simple n:1 integer ratios such as 2:1 (duple meter), 3:1 (triple), or 4:1 (quadruple) [53]. Metric pulsations are experienced as regular series of internal events, with every *n*th event perceived to be accented, i.e., stronger than its neighbors. March, waltz, and salsa music support different types of rhythmic movement coordination partly because each best fits within a different metric framework: duple, triple, and quadruple, respectively.

Metric frameworks facilitate rhythmic perception and action by encouraging listeners and performers to allocate their attentional resources in accordance with periodicities underlying the music's temporal structure [51, 54, 55]. In ensemble performance, metric frameworks may modulate the amount of attention that is available at a particular point in time (via arousal mechanisms) and the amount of attention that is actually invested at this time (via dynamic attending processes) in a manner that is conducive to the flexibility required to integrate information from different sources while tending to a high priority part [48]. Metric resource allocation schemes could thus promote ensemble cohesion by allowing performers to use a common attentional template to accommodate the different surface details of their individual parts.

Support for the hypothesis that metric frameworks play a role in prioritized integrative attention comes from studies designed to capture the cognitive and motor demands of ensemble performance using perception- and production-based behavioral tasks. For instance, in a listening task [54], musicians were required simultaneously to memorize a target (high priority) part and the overall aggregate structure (resulting from the combination of parts) of short percussion duets. Recognition memory for both aspects of each duet was found to be influenced by how well the target part and the aggregate structure could be accommodated within the same metric framework. Analogous results were obtained in a 'rhythmic canon' study that required percussionists to produce memorized rhythm patterns while listening to different patterns, which also had to be subsequently reproduced.

Prioritized integrative attention can be conceptualized as a hybrid mode of attention that occupies the middle ground of a continuum between two pure modes: selective attention and ‘nonprioritized’ integrative attention. The former involves focusing on one instrumental or vocal part to the exclusion of others, whereas the latter involves focusing on the aggregate structure that emerges when all parts are combined with equal weight. Ensemble performance may require individuals to roam the middle ground of the selective-integrative attention continuum to deal with changes in the momentary demands of their own parts and the structural relationship between their own and others’ parts in terms of musical parameters such pitch, rhythm, timbre (instrumental tone color), and balance (relative loudness).

Selective and nonprioritized integrative attention, in addition to standard divided attention (which involves focusing on all parts without necessarily gauging the relation between them), have been investigated in a number of studies relevant to multipart musical listening. The results of these studies suggest that the structural relationship between parts can affect the deployment of attention even when this relationship is not directly relevant to the task at hand (e.g., detecting specific target sounds in one or more parts) [56-58]. Considerable attentional skill may be required to overcome such bottom-up perceptual grouping constraints while engaged in musical joint action. Indeed, proficiency in the use of metric frameworks to guide prioritized integrative attention may be a hallmark of expert ensemble performers and listeners. The degree to which prioritized integrative attending skills generalize to other forms of joint action is presently unknown, although the notion seems plausible. Neuroimaging studies have found that manipulations of attentional strategy in the context of multipart musical listening influence activity in frontal-parietal (including the SMA/pre-SMA and premotor cortex) and temporal regions implicated in attention, working memory, and motor imagery across a variety of domains [59, 60].

14.5 Adapting to others’ action timing

The most fundamental requirement of performance-based musical joint action is the temporal coordination of one’s own movements and sounds with those of others. To satisfy this requirement, individuals must constantly adjust the timing of their movements in order to maintain synchrony in the face of expressively motivated deviations in local tempo (rubato), large-scale tempo changes, and other − often unpredictable − events. Such adaptive timing requires flexible internal timekeepers, i.e., interval generators [61] or oscillatory processes [62] that control the temporal aspects of perception and action. Although issues concerning the instantiation of timekeepers in the brain are far from settled [63], steadily accumulating evidence points towards the involvement of distributed neural circuits comprising motor- and imagery-related areas including the SMA/pre-SMA, premotor regions, the superior temporal gyrus, the basal ganglia, the thalamus, and the cerebellum [64-70]. In musical contexts, the pulsations associated with metric frameworks are driven by hierarchically arranged timekeepers. Oscillatory brain activity that is consistent with metric hierarchies has been detected using electrophysiological techniques with high temporal resolution [71]. The cerebellum may contribute to such oscillatory patterns by entraining the firing rates of neural populations in segregated cortical areas [72]. To enable the production of the non-isochronous rhythms that characterize music, timekeeper networks may recruit prefrontal brain regions that have been implicated in working memory and attention [73, 74].

Musical joint action requires timekeepers in separate individuals to be synchronized, or coupled, with one another. Such coupling is achieved via error correction processes that adjust each individual's timekeeper(s) based on discrepancies between the timing of the individual's actions and those of his or her co-performers. Two independent error correction processes subserve adaptive timing: *Period correction*, which refers to an adjustment of the duration of the timekeeper interval or oscillator period, and *phase correction*, which refers to an adjustment to the way in which the sequence of pulses generated by one timekeeper is aligned against the sequence of pulses generated by another timekeeper. Period correction is required only when there is an obvious change in tempo. Phase correction, on the other hand, is needed constantly because timing discrepancies are inevitable. Note, however, that the resultant asynchronies should not be viewed in a negative light. Music sounds dull without them. Moreover, somewhat paradoxically, there is evidence that asynchronies facilitate, rather than interfere with, covert attentional entrainment and overt movement coordination in musical contexts [55, 75, 76].

Detailed theoretical models of phase and period correction have been developed [77-79], and the distinction between the two processes is supported by findings in various fields. Relevant behavioral research has typically employed experimental paradigms that require isolated individuals to produce movements (e.g., finger taps) in time with computer-controlled pacing sequences (see [80, 81] for comprehensive reviews by Bruno Repp). Such studies have yielded results indicating that phase correction takes place automatically (at least at tempi faster than about 60 beats per minute [82]), whereas period correction requires conscious awareness and attention [83, 84]. Phase correction is more effective with auditory than with visual sequences [85], which highlights its importance in musical synchronization. The results of developmental research suggest that full functionality emerges earlier for phase correction than for period correction in human ontogeny [86, 87], and comparative observations have led to the claim that non-human animals who display group synchrony are only capable of phase correction [88]. Finally, neuroscientific work suggests that phase correction is primarily a cerebellar function while period correction calls upon an additional corticothalamic network that includes the basal ganglia and prefrontal regions [73, 89-91].

During musical joint action, ensemble cohesion may vary as a function of the sensitivity of ensemble members to each other's use of error correction. In a recent study [92], musically trained individuals were required to synchronize finger taps with auditory sequences presented by a computer that was programmed to implement varying degrees of error correction in a manner that was either cooperative (i.e., aimed at reducing asynchronies) or uncooperative (aimed at increasing asynchronies). Analyses of the humans' behavior under these conditions suggested that they engaged in fairly constant, moderate amounts of phase correction so long as the computer was cooperative. When the computer was uncooperative, the humans engaged in more vigorous phase correction, which appeared to be supplemented by intermittent period correction in some situations (most notably when the computer did not implement period correction, and therefore was able to maintain its own stable tempo). To the extent that these findings generalize to ensemble performance, automatically applied phase correction should be sufficient to maintain synchrony in the face of expressive timing deviations. However, when it is difficult to anticipate upcoming expressive timing because the stylistic idiosyncrasies of other ensemble members, or the music itself, are unfamiliar, the performer has the option of intentionally increasing the gain of phase correction and/or engaging strategically in intermittent period correction.

Related work has shown that strategic timekeeper adjustments can be used to stabilize challenging modes of sensorimotor coordination. In a study that required antiphase (off-beat) coordination with an external beat sequence [93], it was found that musicians were able to counteract the compelling tendency to fall onto the beat by engaging in regular phase resetting based on metric structure (which was induced either by physical accents in the pacing sequence or by the instruction to imagine such accents when they were in fact absent).

Although most research that is relevant to adaptive timing during musical joint action has been conducted using paradigms involving isolated individuals moving in synchrony with computer-controlled sequences, inroads have been made into the realm of real, temporally precise interpersonal coordination. Outside the music domain, the dynamics of interpersonal coordination (e.g., during conversation) have been investigated under conditions that vary in terms of the degree to which coupling is intentional and whether it is mediated via visual and/or auditory channels [94-98]. Intriguing electrophysiological work in this vein has revealed that oscillatory neural activity in the mirror system distinguishes between whether or not two peoples' rhythmic finger movements are coordinated when in visual contact [99].

In the music domain, visually mediated coordination has been investigated in research aimed at identifying the kinematic features of a conductor's gestures that musicians use as a basis for synchronization [100]. Coordination via the auditory channel has been addressed recently in finger tapping studies that are directly relevant to adaptive timing. Preliminary results from one such study suggest that each individual from a pair compensates for timing errors produced by their partner, as well as their own errors, when tapping alternately in time with an external beat sequence [101]. Such mutual error correction could serve to make multiple ensemble performers sound as one. Related work addressing the impact of social and developmental factors on interpersonal synchronization is also underway [102, 103].

14.6 Relations between imagery, attention, & adaptive timing

Anticipatory auditory imagery, prioritized integrative attention, and adaptive timing must act together in concert rather than in isolation during musical joint action. In this section, the results of a new study that investigated how the mechanisms underlying these three ensemble skills interact to determine coordination in piano duos are briefly reported.

The body movements of seven pairs of expert pianists were recorded using a motion capture system while they performed unfamiliar duets on a pair of MIDI pianos. Analyses of the pianists' movements revealed that anterior-posterior body sway was more strongly correlated in some pairs than in others. These differences between pairs provided an index of musical synchronization that was both reliable (i.e., constant across contrasting musical pieces and independent of whether or not pianists were in visual contact) and valid (i.e., body sway coordination was negatively correlated with the degree of asynchrony between sounds, which was calculated from the MIDI recordings).

Several months after recording the duets, the same 14 pianists were invited back individually to complete experimental tasks designed to assess their abilities at anticipatory auditory imagery, prioritized integrative attention, and adaptive timing. The tasks were borrowed from previous studies addressing these cognitive processes. The anticipatory auditory imagery task, which involved the production of rhythmic movement sequences with predictable compatible or incompatible auditory effects (see [25]), yielded an index reflecting the vividness of imagery for upcoming musical sounds. The prioritized integrative attention task (see Experiment 1 in [54]) yielded an index of the strength of the relationship between prioritized integrative attending and metric structure. The adaptive timing task, which involved finger tapping in time with computer-controlled auditory sequences (see [84]), assessed the speed and completeness of adaptation to tempo changes.

Although anticipatory auditory imagery, prioritized integrative attention, and adaptive timing indices were not strongly correlated with one another across individual pianists, the three indices combined well to predict the observed differences in body sway coordination between pairs of pianists (see Figure 1).

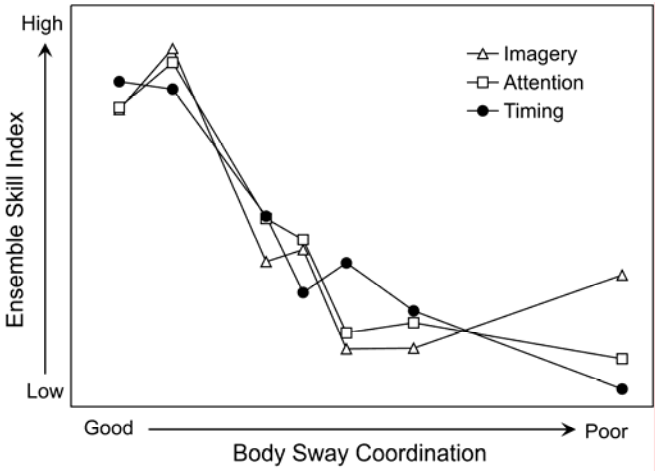

Figure 1. Scatter plot showing the relationship between body sway coordination (ranging from good to poor on the horizontal axis) and indices of abilities related to three ensemble skills—anticipatory auditory *imagery*, prioritized integrative *attention*, and adaptive *timing* (ranging from low to high on the vertical axis)—for seven pairs of pianists. For imagery and attention, each data point represents the mean score for a pair of pianists. For timing, each data point represents the higher of the two scores from a pair. Note that all measures were normalized (hence the units are arbitrary) so that they could be plotted in the same range.

Interestingly, the integrity of these predictions did not necessarily rely upon the inclusion of indices from both members of a pair. Four statistical models that differed in terms of the indices that they included were considered. Two models included indices from both members of each pair, either averaged or differenced, and two included indices from just a single member, either the pianist with the highest or the lowest score on each index. The models based on averaged indices and maximum scores accounted for comparably high amounts (each over 90%) of the variance in body sway coordination (while the remaining models were less predictive). Thus, good coordination required at least one member of a pair to have relatively good ensemble skills. Adaptive timing stood out in this regard when the relation between each skill and coordination was considered separately. Here the maximum score from a pair was a stronger determinant of coordination than the averaged score. This may reflect the tendency for individuals to adopt roles as 'leaders' and 'followers' during ensemble performance [10]. Coordination in duos may be good to the extent that the follower is able to anticipate and adapt to the leader's expressive timing nuances while the leader concentrates on shaping the music rather than on adaptive timing. Indeed, the results of the cooperative/uncooperative computer study [92] described earlier are consistent with the notion that that sensorimotor synchronization is facilitated by such an asymmetry in the coupling between two parties in a dyad.

Although strong conclusions should not be drawn based on observations from just seven pairs of pianists, the results of this study suggest that it is worthwhile to pursue a model of musical joint action with anticipatory auditory imagery, prioritized integrative attention, and adaptive timing at its core. (It should be noted that alternative models with predictors such as sensitivity to the compatibility between movements and actual rather than anticipated sounds, prioritized integrative attending in contexts lacking clear metric structure, and synchronization accuracy in the absence of tempo changes were tested, but they did not fare well.)

The precise nature of the relationship between the cognitive processes in the proposed model remains to be specified. Previous studies examining the relationship between anticipatory imagery and attention outside the music domain have shown that the preparatory activation of sensory areas via imagery boosts neural responses to attended stimuli [104]. Furthermore, the results of work on the relationship between attention and internal timing mechanisms suggest that such preparatory baseline shifts in attention can come to occur in a self-sustained, period manner [50, 51]. It is assumed here that anticipatory auditory imagery facilitates prioritized integrative attention similarly during musical joint action, and that timing mechanisms assist by regulating the relationship between imagery and attentional processes both within and between individuals. Specifically, anticipatory auditory imagery and prioritized integrative attention are linked through the use of common timekeepers to drive forward and inverse internal models within an individual. The error correction processes that mediate adaptive timing may then ensure that these time-locked internal models are coupled between individuals engaged in musical joint action.

Overlap in the brain areas subserving imagery, attention, and timing—with the SMA/pre-SMA, premotor regions, and the cerebellum being prominent in this regard—is broadly consistent with this sketch. Reviews of the neuroscience of music literature have identified these areas (among others such as the superior temporal gyrus and the sensorimotor cortex) as being of central importance in meeting the sequencing, timing, and sensorimotor integration needs that arise during music perception and production [105, 106]. Individual differences in ensemble expertise may be related to the degree of entrainment between the different neural populations comprising such a core network and the additional brain regions it recruits during musical joint action.

14.7 Conclusions

Musical joint action showcases the human capacity for temporally precise yet flexible interpersonal coordination. These qualities are exemplified in musical ensembles. Ensemble cohesion requires individual performers to (1) share common goal representations of the ideal sound, and (2) possess a suite of ensemble skills − basic cognitive processes relating to anticipatory auditory imagery, prioritized integrative attention, and adaptive timing − that enable these goals to be realized. Additional considerations, including social factors, knowledge of the music, and familiarity with the stylistic tendencies of one’s co-performers, may impact upon ensemble cohesion by affecting these three basic processes. Thus, imagery, attention, and adaptive timing may come to modulate the mutual awareness − and interpretation − of co-performers’ actions, thereby setting the stage for joint enaction and intersubjectivity.

The proposed mechanisms underlying anticipatory auditory imagery, prioritized integrative attention, and adaptive timing include coupled forward and inverse internal models, metric schemas that modulate autonomic arousal and the intensity of attentional focus, and internal timekeepers capable of automatic and intention-based forms of error correction. It is a challenge for future research to delve deeper into the issue of how these mechanisms interact to determine the quality of musical coordination. Pursuing this challenge should prove that musical joint action is a fruitful domain in which to investigate the cognitive processes and neural mechanisms that support interactive enaction and intersubjectivity.

14.8 Acknowledgements

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14.9 References

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