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Temporal coordination between performing musicians

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Many common behaviours require people to coordinate the timing of their actions with the timing of others' actions. We examined whether representations of musicians' actions are activated in coperformers with whom they must coordinate their actions in time and whether coperformers simulate each other's actions using their own motor systems during temporal coordination. Pianists performed right-hand melodies along with simple or complex left-hand accompaniments produced by themselves or by another pianist. Individual performers' preferred performance rates were measured in solo performance of the right-hand melody. The complexity of the left-hand accompaniment influenced the temporal grouping structure of the right-hand melody in the same way when it was performed by the self or by the duet partner, providing some support for the action corepresentation hypothesis. In contrast, accompaniment complexity had little influence on temporal coordination measures (asynchronies and cross-correlations between parts). Temporal coordination measures were influenced by a priori similarities 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. These findings extend previous findings of action corepresentation and action simulation to a task that requires precise temporal coordination of independent yet simultaneous actions.

Keywords: Temporal coordination; Synchronization; Joint action; Action simulation; Music performance.

Many common behaviours such as moving a table, rowing a boat, or producing music require individual performers to coordinate their actions with others. There has recently been a surge of research examining the basic mechanisms of perception and action that support these types of joint action (see Knoblich, Butterfill, & Sebanz, 2011, for a review). The current study examines two mechanisms that have been proposed to support joint

action. The first mechanism, action corepresentation, concerns *what* kinds of action an interaction partner will produce; the second mechanism, action simulation, concerns *when* an interaction partner will produce actions (Sebanz & Knoblich, 2009). Evidence for corepresentation has been shown primarily in tasks that require people to take turns producing actions (Sebanz, Knoblich, & Prinz, 2003; Tsai, Kuo, Jing, Hung, & Tzeng,

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2006). The first goal of the current study was to determine whether corepresentation is also evident in tasks such as ensemble music performance, which require people to produce independent, often simultaneous, actions that are precisely coordinated in time (Palmer, 1997). Evidence for the second mechanism, action simulation, has primarily been shown when people observe or coordinate with previously recorded actions (Aglioti, Cesari, Romani, & Urgesi, 2008; Keller, Knoblich, & Repp, 2007). The second goal of the current study was to examine action simulation during dynamic temporal coordination between partners who may adapt in real time to each other's changing actions.

Action corepresentation

Action corepresentation refers to the hypothesis that people engaging in a joint action activate mental representations not only of their own task but of their partner's task as well (Sebanz et al., 2003; Tsai et al., 2006; Vesper, Butterfill, Knoblich, & Sebanz, 2010). This hypothesis stems from research showing that observing or predicting another person's actions activates corresponding action representations in the observer. In monkeys, the same neurons discharge when an action is observed as when it is executed (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). In humans, similar brain regions are activated when an action is perceived as when it is executed (Rizzolatti & Craighero, 2004). Another person's potential action also activates representational structures in an observer: The motor cortex is activated when a movement is predicted but has yet to be observed (Kilner, Vargas, Duval, Blakemore, & Sirigu, 2004), and similar neural mechanisms underlie error detection in observed and executed actions (van Schie, Mars, Coles, & Bekkering, 2004).

One person's potential actions also activate representational structures in another person when the two take turns performing a task. In reaction time tasks in which stimulus characteristics specify which of two action alternatives has to be produced, an irrelevant stimulus dimension produces similar interference effects (a) when one person is

responsible for producing both action alternatives and (b) when the task is distributed among two performers, each of whom is responsible for producing only one of the two alternatives (Sebanz et al., 2003; Tsai et al., 2006). These findings suggest that each person represents both action alternatives in the shared task, as they do in the individual task. The cop performer's actions need not be observed for interference to occur (Tsai, Kuo, Hung, & Tzeng, 2008), and both performers can also form representations of the particular task rules under which the other person performs (Sebanz, Knoblich, & Prinz, 2005). Furthermore, similar event-related potentials (ERPs) are elicited by stimuli that refer to a performer's task and to his or her cop performer's actions (Sebanz, Knoblich, Prinz, & Wascher, 2006; Tsai et al., 2006). Together, these findings indicate that people working side by side activate representations of each other's actions, even when their actions need not be coordinated.

The first goal of the present experiment was to examine whether representations of another person's actions are activated when people must produce actions that are independent but coordinated in time. We addressed this question in ensemble music performance, which requires precise temporal coordination between performers who produce separate but simultaneous musical sequences. Given that representations of others' actions are activated in turn-taking tasks in which a cop performer's actions are *irrelevant* to one's own task (Sebanz et al., 2003; Tsai et al., 2006), we expected that representations of others' actions would also be activated during coordination tasks such as duet piano performance, in which a cop performer's actions are *directly relevant* to one's own task.

Action simulation

Action simulation refers to the hypothesis that people use their own motor systems to simulate their partner's actions, thereby allowing them to predict when those actions will occur (Bekkering et al., 2009; Sebanz & Knoblich, 2009). This hypothesis stems from research indicating that people use internal forward models, which predict the sensory consequences of outgoing motor

commands, to control their own movements (Miall & Wolpert, 1996; Wolpert & Flanagan, 2001; Wolpert & Kawato, 1998). It has been proposed that people also use these forward models to predict the consequences of other people's actions (Wilson & Knoblich, 2005; Wolpert, Doya, & Kawato, 2003).

Several findings support the hypothesis that people simulate the outcome of other people's actions using their own motor systems. First, an observer's action repertoire influences the activation of motor areas during action observation: Significantly more premotor activity occurs when people observe actions that they are experts at producing than when they observe actions with which they have less experience (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006). Second, people who have extensive experience producing an action are better able to predict the outcome of similar actions than people who have comparable experience observing, but not producing, that action (Aglioti et al., 2008). Third, people are better at predicting the outcomes of observed actions when those actions were self-generated than when they were produced by another person (Knoblich & Flach, 2001; Knoblich, Seigerschmidt, Flach, & Prinz, 2002). People are also better able to coordinate the timing of their actions with self-generated than other-generated actions, as evidenced by pianists' greater synchronization accuracy when performing along with previously recorded pieces performed by themselves than with those by other performers (Keller et al., 2007). Thus, actions that are more similar to the observer's action repertoire allow for more accurate simulation of both expected action outcomes and expected action timing.

The second goal of the current study was to examine the action simulation hypothesis during online action coordination between two performers, rather than during coordination with previously recorded action sequences. Given that people's predictions about observed or heard actions are better the more similar those predicted actions are to their own action production (Aglioti et al., 2008; Keller et al., 2007; Knoblich

& Flach, 2001; Knoblich et al., 2002), we predicted that partners who are more similar to each other during solo performance would be better able to coordinate with each other during joint performance.

Aims and hypotheses

The current experiment was designed to examine the action corepresentation and action simulation hypotheses in duet music performance that requires precise temporal coordination between partners. In order to test the hypothesis that representations of others' actions are activated during a temporal coordination task, we employed a set of conditions similar to those employed by Sebanz et al. (2003), in which an irrelevant stimulus dimension produced similar interference effects both when one person produced both right and left button presses in response to visual stimuli and when one person produced one button press while their partner was responsible for the other. The analogous conditions employed in the current experiment were a bimanual condition, in which one participant simultaneously performed a right-hand and a left-hand melody, and a joint condition, in which the right-hand melody was produced by one participant and the left-hand melody by another participant. We manipulated the left-hand melody so that it contained either a simple sequence of repetitive pitch changes or a more complex melodic sequence. We expected the melodic and harmonic structure of the left-hand melody to influence temporal characteristics of the right-hand melody in the bimanual condition, based on previous work in piano performance and other finger tapping tasks (Collard & Povel, 1982; Loehr & Palmer, 2007; Palmer, 1989; Povel & Collard, 1982). If the melodic and harmonic structure of the left-hand melody has the same influence on temporal characteristics of the right-hand melody in the joint condition as in the bimanual condition, this would provide evidence that the performer responsible for the right-hand part activated representations of the left-hand part produced by his or her partner (Sebanz et al., 2003).

In order to examine the action simulation hypothesis, we measured each participant's solo performance of the right-hand melody without any accompaniment and then calculated the similarity (match) between the performers in each duet pair. Participants were randomly assigned to pairs in order to mimic the range of matches between performers that might naturally occur in ensemble music performance. Match between partners was calculated in terms of participants' preferred solo performance rate relative to an initial metronome that was sounded (and then turned off) before each performance began. This implementation simulated typical duet performance, in which the performance rate is set initially by one or both performers. We expected that partners who were more similar to each other in terms of solo performance rates would be better able to simulate each other's performances and would therefore be more closely coordinated and better able to adapt to each other's performance timing during the joint performances.

Method

Participants

Thirty-two pianists (15 male), ranging in age from 18 to 37 years ($M = 22.44$, $SD = 4.13$), were recruited from the Montreal community. Each participant was randomly paired with another pianist to form 16 pairs of pianists. All participants had received at least 10 years of private piano lessons ($M = 15.11$, $SD = 3.38$), and all but two were right-handed. None of the pairs had performed music together prior to the experiment. All participants gave informed consent according to procedures reviewed by the Institutional Review Board of McGill University.

Stimulus materials

Four isochronous 16-tone melodies were constructed that were easy to perform with the right hand and could be continuously repeated. Two isochronous left-hand parts were created to accompany each right-hand melody. The *simple left-hand accompaniment* consisted of a sequence of simple repetitive pitch changes that reinforced the

simple four-beat harmonic structure of the right-hand melody. The *complex left-hand accompaniment* consisted of a more complex melody with scalar (linear) pitch motion that resulted in a more polyphonic musical style when played together with the right-hand melody. Both right- and left-hand parts were designed to require no hand repositioning and equivalent hand stretching (pitch intervals) and thus required no differences in movement amplitude. Repeating pitches and large pitch intervals involving the ring or pinky finger were avoided, because they can cause timing delays due to biomechanical constraints (Loehr & Palmer, 2009). One right-hand melody and its two left-hand accompaniments are shown in Figure 1.

Equipment

Melodies were performed on a Roland RD-700SX (Roland Corporation, Los Angeles, CA, USA) weighted-key digital piano. Presentation of auditory feedback and metronome pulses, as well as MIDI data acquisition, was implemented via the FTAP software program (Finney, 2001). Timbres were generated by an Edirol StudioCanvas SD-80, using a piano timbre from the Contemporary bank for performances (Rock Piano, Instrument No. 002) and a drum timbre from the Classical bank (Standard Set, Note 33) for the metronome pulses. The participants heard performances and metronome pulses over two speakers placed in front of the keyboard. The volume was adjusted to a comfortable level for each pair of participants.

Design and procedure

Each participant produced two of the right-hand melodies in three performance conditions in a within-subjects design. In the *control* condition, participants produced the right-hand melody alone, with no left-hand accompaniment. In the *bimanual* condition, participants produced the right-hand melody along with a left-hand accompaniment produced by themselves. In the *joint* condition, participants produced the right-hand melody along with a left-hand accompaniment produced by the other pianist in the pair. Both left-hand accompaniments (simple and complex) were



Figure 1. One right-hand (R.H.) stimulus melody (top panel) and its simple (middle panel) and complex (bottom panel) left-hand (L.H.) accompaniments.

performed in both the bimanual and joint performance conditions. Participants always performed the control condition both before and after the remaining experimental conditions. Because solo performance rates in the two control conditions were highly correlated ($r = .75$, $p < .001$), we report measures from the initial performances only. The order of the remaining conditions (bimanual and joint performances with simple and complex left-hand accompaniments) was counterbalanced across duet pairs.

Participants first completed a musical background questionnaire and performed a screening melody to ensure they could perform the experimental melodies within two or three minutes of practice. Participants were then seated side by side at the piano. The testing procedure began with the control condition. First, one of the participants practised one of the right-hand melodies without a metronome; practice continued until the participant could perform the melody without any errors. This was followed by paced practice trials that were preceded by an initial metronome, which was sounded eight times at 400-ms interonset intervals (IOIs) at the beginning of each trial and was then turned off. Participants were instructed to perform the melody at the pace set by the initial metronome until they were told to stop after two error-free repetitions. Two test trials were then recorded in which the participant performed the melody at the pace set by the initial metronome; each test trial lasted until four

error-free repetitions of the melody had been performed. The two participants then switched places, and the entire procedure was repeated with the second participant performing a new right-hand melody. The participants then switched places twice more, so that each participant performed two right-hand melodies. The four melodies were presented in a random order, which was reversed for half of the pairs.

The stimulus order in the control condition was then repeated in the bimanual and joint conditions. In the joint condition, participants were instructed to play together while following the pace set by the initial metronome. In both the bimanual and joint conditions, participants first practised the right-hand melody alone, the left-hand accompaniment alone, and then both parts simultaneously, all without an initial metronome. Participants then practised both parts simultaneously, following an initial metronome. The presence of the partner during all experimental conditions controlled for potential social facilitation effects (Vesper, Soutschek, & Schubö, 2009), and numerous repetitions of both musical parts during bimanual and joint practice ensured that participants could form a representation of the pitches and movements to be produced by their partners before the test trials began. After the experimental conditions had been completed, the participants repeated the control condition. Participation in the experiment took approximately two hours, and participants received a nominal fee.

Data analysis

A total of 64 keystrokes were included per trial (16 keystrokes for each of the four repetitions). Eighteen trials (2.34% of the total trials) contained errors that had not been detected by the experimenter during testing; these trials were excluded from analysis. Timing analyses were based on MIDI tone onset times (1-ms temporal resolution).

Results

Action corepresentation

Analysis strategy. We first addressed the hypothesis that differences between simple and complex left-hand accompaniments in the bimanual performance condition would also be present in the joint performance condition. We thus conducted analyses of variance (ANOVAs) by left-hand accompaniment (simple, complex) and performance condition (bimanual, joint) on measures of performance timing taken from each right-hand melody (which did not change across the four conditions). Three measures of performance timing were examined: temporal grouping structure (Collard & Povel, 1982; Loehr & Palmer, 2007), melody lead (Palmer, 1989, 1996), and tracking between the melody and accompaniment (Goebel & Palmer, 2009). Each measure was expected to yield differences between the left-hand accompaniments in the bimanual condition based on previous work in piano performance and tapping tasks; specific hypotheses for each measure are described below. Each measure was expected to yield the same pattern of differences between left-hand accompaniments in the joint condition as that in the bimanual condition, resulting in a main effect of left-hand accompaniment in each ANOVA and no interaction with performance condition. There were no condition order effects of the left-hand accompaniment on any of the variables.

Temporal grouping. We first examined whether the pattern of IOIs in the right-hand melody differed depending on the left-hand accompaniment. The pattern of IOIs in tapping tasks has been shown to reflect the grouping structure of sequence elements (Collard & Povel, 1982; Loehr &

Palmer, 2007; Povel & Collard, 1982). We expected participants to produce the melody tones in groups of four, consistent with the metrical structure and implied harmony of the music. We expected the four-beat grouping to be stronger when the right-hand melody was accompanied by the simple left-hand part, which contained harmonic transitions every four beats, than when the right-hand melody was accompanied by the complex left-hand part, which contained more transitions and thus had a less salient four-beat harmonic structure.

We measured grouping strength by calculating autocorrelations in the time series of IOIs from each right-hand melody. IOIs were defined as current keypress onset time minus preceding keypress onset time. Autocorrelations were calculated by correlating the time series of IOIs with itself at different lags. We first calculated autocorrelations at Lags 1 through 8 separately for each trial. The maximum positive mean autocorrelation occurred at Lag 4 ($M = .17$, $SE = .0096$) and was significantly greater than zero, $F(1, 31) = 187.20$, $MSE = 0.020$, $p < .001$. Thus, participants produced the same pattern of IOIs every four events, consistent with the metrical and harmonic structure of the music. Figure 2 shows the mean Lag 4 autocorrelations in the bimanual and joint conditions. The tendency to pattern the IOIs in groups of four was stronger when the right-hand melody was performed with a complex left-hand accompaniment than when it was performed with a simple

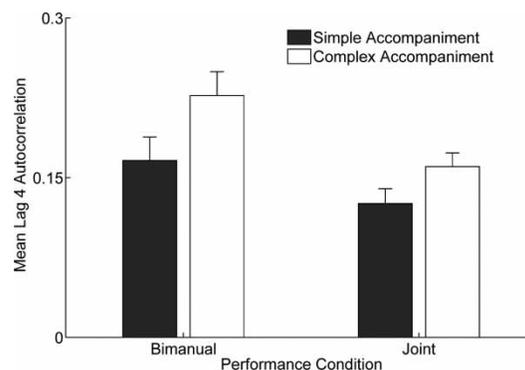


Figure 2. Mean Lag 4 autocorrelations in right-hand melodies ($\pm SE$) by left-hand accompaniment and performance condition.

left-hand accompaniment, in both the bimanual and joint conditions. In addition, the tendency to pattern the IOIs in groups of four was stronger in the bimanual condition (when the same performer produced both parts) than in the joint condition. An ANOVA by performance condition (bimanual, joint) and left-hand accompaniment (simple, complex) on the Lag 4 autocorrelations confirmed the significant effects of left-hand accompaniment, $F(1, 31) = 10.72$, $MSE = 0.0068$, $p < .004$, $\eta^2 = .78$, and performance condition, $F(1, 31) = 7.86$, $MSE = 0.012$, $p < .01$, $\eta^2 = .89$, with no significant interaction, $F(1, 31) = 1.13$, $MSE = 0.0049$, $p > .29$, $\eta^2 = .18$. Follow-up ANOVAs examining the effects of left-hand accompaniment separately for the bimanual and joint conditions confirmed significant effects in both the bimanual, $F(1, 31) = 7.95$, $p < .01$, and joint, $F(1, 31) = 4.48$, $p < .05$, conditions. Thus, the left-hand accompaniment had the same influence on the right-hand performance regardless of whether it was produced by oneself or by another performer, consistent with the action corepresentation hypothesis.

Melody lead. We next examined asynchronies between the right-hand melody and left-hand accompaniment in each condition. We expected that tones in the right-hand melody would be produced earlier than tones in the left-hand accompaniment, based on previous work showing that melody tones tend to be played earlier than non-melody tones (melody lead; Palmer, 1989). We expected a larger melody lead when the right-hand melody was performed with a simple left-hand accompaniment than when it was performed with a complex left-hand accompaniment, as the complex left-hand accompaniment suggests a more polyphonic musical style, which typically reduces melody lead (Large & Palmer, 2002; Palmer, 1989).

Figure 3 shows participants' mean asynchronies, defined as right-hand keystroke onset time minus left-hand keystroke onset time. Negative values indicate that the right-hand keystrokes preceded the left-hand keystrokes. Participants' mean asynchronies were smaller (more negative) when the right hand was accompanied by a simple left-hand

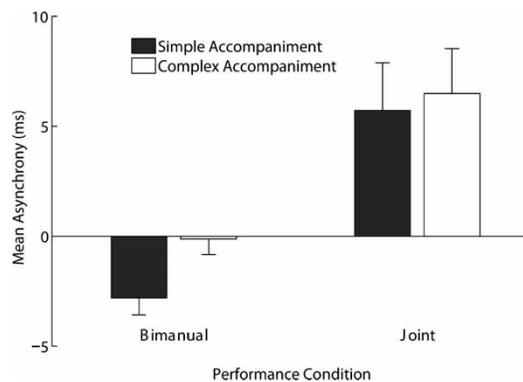


Figure 3. Mean asynchronies ($\pm SE$) by left-hand accompaniment and performance condition.

accompaniment than when it was accompanied by a complex left-hand accompaniment. However, mean asynchronies were negative, indicating melody lead, in the bimanual condition only. An ANOVA by performance condition (bimanual, joint) and left-hand accompaniment (simple, complex) confirmed the significant effects of performance condition, $F(1, 31) = 11.71$, $MSE = 156.87$, $p < .003$, $\eta^2 = .91$, and left-hand accompaniment, $F(1, 31) = 7.97$, $MSE = 12.03$, $p < .009$, $\eta^2 = .78$, with no significant interaction, $F(1, 31) = 3.21$, $MSE = 9.18$, $p > .08$, $\eta^2 = .41$. Follow-up ANOVAs examining the effects of left-hand accompaniment separately for the bimanual and joint conditions confirmed the effect of accompaniment within the bimanual condition, $F(1, 31) = 23.87$, $p < .001$, but not within the joint condition, $F(1, 31) = 0.58$, $p = .45$, indicating that the effect of the left-hand accompaniment was largely due to the bimanual condition.

Tracking between melody and accompaniment. Finally, we examined cross-correlations between the time series of the right-hand melody and the left-hand accompaniment. Cross-correlations at Lag 0, computed between the right-hand melody's IOI_1, \dots, IOI_n and the left-hand accompaniment's IOI_1, \dots, IOI_n (where n is the number of notes in the melody), measure the degree to which IOI patterns change simultaneously in the right- and left-hand parts. Lag +1 cross-correlations—

computed between the right-hand melody's $IOI_{1, \dots, (n-1)}$ and the left-hand accompaniment's $IOI_{2, \dots, n}$ —measure the degree to which IOI patterns in the accompaniment follow the IOI patterns of the right-hand melody at a delay of one tone, and Lag -1 cross-correlations—computed between the left-hand accompaniment's $IOI_{1, \dots, (n-1)}$ and the right-hand melody's $IOI_{2, \dots, n}$ —measure the degree to which IOI patterns in the melody follow the IOI patterns of the left-hand accompaniment at a delay of one tone. Positive Lag +1 cross-correlations thus indicate that the timing profile of the accompaniment tracks or imitates the timing profile of the melody; positive Lag -1 cross-correlations indicate the reverse (Goebel & Palmer, 2009). Positive cross-correlations at both Lags +1 and -1 indicate two-way tracking or mutual adaptation between performers (Goebel & Palmer, 2009; Konvalinka, Vuust, Roepstorff, & Frith, 2010). We expected the timing profile of the accompaniment to track that of the melody more strongly when the melody was performed with a simple left-hand part, which more clearly differentiates between melody and accompaniment, than when it was performed with a complex left-hand part, which suggests a more polyphonic style.

Figure 4 shows the cross-correlations for the bimanual (top panel) and joint (bottom panel) conditions. The figure shows that correlations were largest at Lag 0 in the bimanual condition, indicating simultaneous timing changes in the two hands of a single performer. In contrast, correlations were larger at Lags +1 and -1 in the joint condition, indicating two-way tracking between the timing of two different performers. The patterns of correlations did not differ when the right-hand melody was accompanied by a simple versus complex left-hand accompaniment, in either the bimanual or the joint conditions. An ANOVA by performance condition (bimanual, joint), left-hand accompaniment (simple, complex), and lag (-1, 0, +1) indicated a main effect of performance condition, $F(1, 31) = 24.32$, $MSE = 0.015$, $p < .001$, and confirmed the performance condition by lag interaction, $F(2, 62) = 351.94$, $MSE = 0.017$, $p < .001$. There was no main effect of left-hand accompaniment, $F(1, 31) = 0.13$, $p > .71$, nor

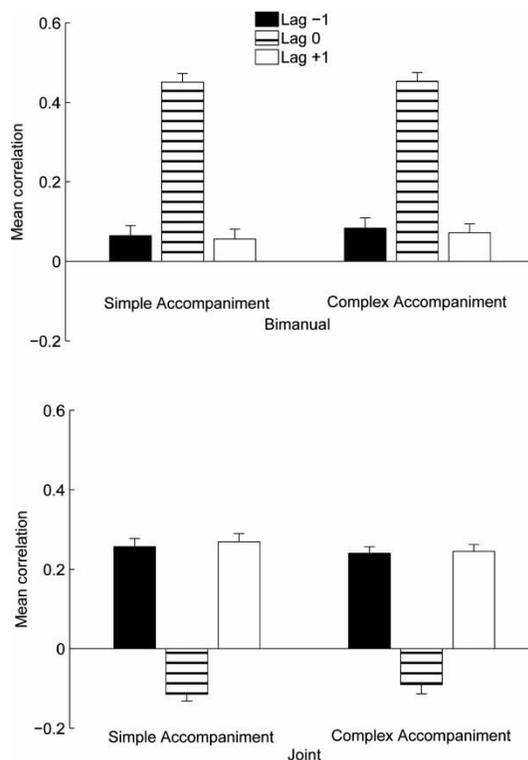


Figure 4. Mean cross-correlations between right-hand melody and left-hand accompaniment ($\pm SE$), by left-hand accompaniment in the bimanual (top panel) and joint (bottom panel) conditions.

were there any interactions with left-hand accompaniment, $F_s < 1.0$, $p_s > .24$. Post hoc analyses confirmed that the Lag 0 correlation was significantly greater than the Lag +1 and Lag -1 correlations in the bimanual condition, and that the Lag +1 and Lag -1 correlations were greater than the Lag 0 correlations in the joint condition. Thus, cross-correlations between hands indicated significant coordination differences between bimanual and joint performances, which we pursue below. Lag +1 and Lag -1 correlations did not differ from each other within either the bimanual or the joint condition (Tukey's honestly significant difference, $HSD = 0.066$).

Action simulation

Analysis strategy. We next addressed the hypothesis that the match between partners' solo performances

would determine how well they were able to coordinate with each other during joint performances. We first determined each participant's preferred solo performance rate and calculated the *mismatch* between partners as the difference between their preferred rates. We then examined the relationship between the solo performance measures and two aspects of joint performance: how well-synchronized partners were (asynchronies), and the degree to which partners tracked each other's timing (cross-correlations). We expected that pairs who were less well matched would be less well synchronized and would show unidirectional tracking (a leader–follower relationship wherein one partner tracks the other's timing; Goebel & Palmer, 2009) rather than mutual tracking or adaptation between partners.

Mismatch between partners. Participants' preferred rates were defined as each participant's mean IOI in the control condition (in which each pianist performed right-hand melodies alone). We refer to the participant within each pair who had the slower preferred rate as the “slower performer” and to the participant with the faster preferred rate as the “faster performer”. There were no differences in musical training between the slower ($M = 15.00$ years of musical training) and faster ($M = 15.22$ years) members of the pairs, $t(30) = -0.18$, $p > .8$. Mismatch between the participants in each pair was calculated as the slower performer's

preferred rate (mean IOI) minus the faster performer's preferred rate (mean IOI). Figure 5 shows the preferred rate of each person in each pair, ordered by degree of mismatch (smallest to largest mismatch from left to right). The dashed line indicates the instructed performance rate (400 ms/IOI). Participants' preferred rates ranged from 357 to 420 ms ($M = 383.73$ ms), and the mismatch between partners ranged from 0.5 to 35 ms ($M = 13.10$ ms).

Joint performance measures. We measured each pair's joint performance in terms of the slower performer relative to the faster performer, regardless of which part (right-hand melody or left-hand accompaniment) each participant performed. We evaluated the joint performance in terms of three variables. First, *overall asynchrony* was defined as the slower performer's keypress times minus the faster performer's keypress times, averaged across all beats in a trial. Positive values indicate that the faster performer's keystrokes preceded the slower performer's keystrokes. Second, *final asynchrony* was defined as the average asynchrony over the final eight beats of the trial, by which time participants were expected to have reached a steady state of coordination. Third, the *cross-correlation difference* was defined as the Lag -1 cross-correlation—slower performer's $IOI_1, \dots, (n-1)$ correlated with faster performer's IOI_2, \dots, n —minus the Lag $+1$ cross-correlation—faster performer's $IOI_1, \dots, (n-1)$

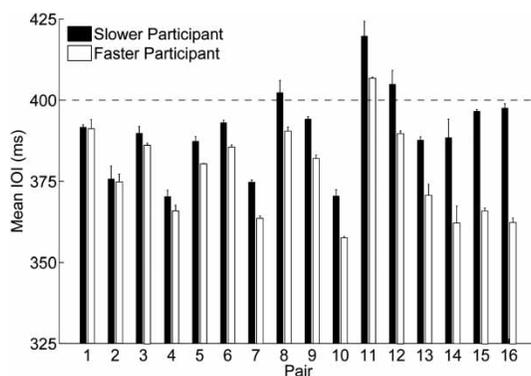


Figure 5. Slower and faster performers' preferred rates, ordered by the size of the difference (slower – faster) between the performers in each pair. The dashed line indicates the instructed performance rate.

correlated with slower performer's IOI_{2, . . . n}—between the two participants' timing profiles. Lag -1 cross-correlations indicate that the faster performer's IOIs imitated the slower performer's IOIs, and Lag +1 cross-correlations indicate the reverse. Cross-correlations at both lags were significantly greater than 0—Lag -1: $M = 0.25$, range = 0.093–0.38, $t(31) = 19.70$, $p < .001$; Lag +1: $M = 0.26$, range = 0.072–0.44, $t(31) = 15.02$, $p < .001$ —indicating bidirectional influence between performers. Difference scores, (Lag -1) - (Lag +1), near zero therefore indicate mutual tracking between performers, positive difference scores indicate stronger tracking of the slower performer by the faster performer than vice versa, and negative difference scores indicate stronger tracking of the faster performer by the slower performer.¹

The correlations between the three measures of joint performance and the three measures of preferred rate (the slower performer's preferred rate, the faster performer's preferred rate, and the mismatch between the two) are shown in Table 1. Mismatch between partners was positively correlated with the final asynchrony and the cross-correlation difference. In contrast, neither the Slower nor the Faster Performer's solo preferred rates correlated with the joint performance measures. Thus, the mismatch between the performers in each pair, rather than characteristics of either individual alone, influenced the temporal characteristics of the joint performances. Larger mismatch was associated with larger positive asynchronies (indicating that the Faster Performer's keystrokes preceded those of the Slower Performer) at the end of each trial. Larger mismatch was also associated with the

Table 1. Correlations between individual difference and joint performance measures

Initial individual differences	Joint performance measures		
	Overall asynchrony	Final asynchrony	Cross-correlation difference
Slower Partner's Preferred Rate	.20	.20	.32
Faster Partner's Preferred Rate	.06	-.06	-.03
Mismatch (Slower-Faster)	.18	.41*	.46*

* $p < .05$.

Faster Performing tracking the timing profile of the Slower Performer more so than vice versa.

The effects of mismatch between partners on their joint performances are illustrated in Figure 6, which shows the final asynchrony (top panel) and Lag -1 and Lag +1 cross-correlations (bottom panel) for the pairs with smallest and largest mismatches. The top panel shows that the pair with the smallest mismatch was better-synchronized than the pair with the largest mismatch. The bottom panel shows that the pair with the smallest mismatch had similar lag -1 and lag +1 cross-correlations, indicating nearly equivalent tracking between the two performers, whereas the pair with the largest mismatch showed a stronger lag -1 than lag +1 cross-correlation, indicating more unidirectional tracking of the Slower Performer by the Faster Performer. To confirm that group differences existed in the Joint performance measures based on the degree of mismatch between

¹ To investigate whether the findings differed depending on which participant performed the left or right hand part, we compared the joint performance measures when the faster performer performed the right hand (and the slower performer performed the left hand) with when the faster performer performed the left hand. Mean overall asynchronies were near zero ($M = -0.12$, $SE = 1.98$) when the faster performer performed the right-hand melody, but were positive ($M = 12.19$; $SE = 1.62$) when the faster performer performed the left-hand accompaniment. This difference was significant in an ANOVA by faster performer's part (right hand, left hand) and left-hand accompaniment (simple, complex), $F(1, 30) = 12.14$, $MSE = 199.79$, $p < .003$. The left-hand lead that occurred in joint performances was thus driven by the faster performers playing the left-hand part. A similar effect was also evident in the mean final asynchrony ($M = -2.00$, $SE = 2.10$, and $M = 11.50$, $SE = 1.71$, when the faster performer performed the right- and left-hand parts, respectively, $F(1, 30) = 13.93$, $MSE = 209.36$, $p < .002$). However, the assignment of performer to part (right vs. left hand) did not affect the cross-correlation difference. Correlational analyses conducted separately for performances in which the faster participant performed the right-hand or the left-hand part yielded equivalent results; we therefore report the combined analysis.

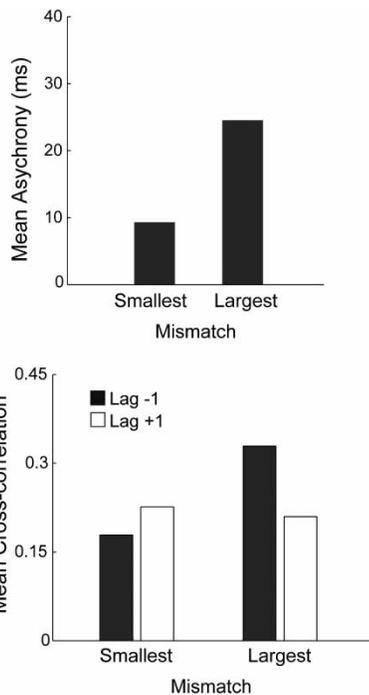


Figure 6. Final asynchrony (top panel) and cross-correlations (bottom panel) for the pairs with smallest and largest mismatch.

partners, a median split of the duet pairs was performed. Means for the two groups (Smaller and Larger mismatch) are shown in Table 2 for each joint performance variable. Differences between means were significant for initial mismatch, $F(1, 14) = 16.45$, $MSE = 50.60$, $p < .001$, final asynchrony, $F(1, 14) = 4.48$, $MSE = 74.65$, $p = .05$, and cross-correlation differences, $F(1, 14) = 6.24$, $MSE = 0.0046$, $p < .03$. Furthermore, mean values of final asynchrony and cross-correlation difference did not differ from zero for pairs with smaller mismatch, but were greater than zero for pairs with larger mismatch. These analyses confirm the hypothesis that pairs who were better matched in preferred rate were better synchronized and showed mutual adaptation in joint performance, compared to pairs who were less well matched.

Discussion

Pianists' duet performances revealed some support for the hypothesis that representations of

Table 2. Mean values (\pm SE) of mismatch and joint performance measures based on a median split of mismatch

Mismatch (ms)	Joint performance measures	
	Final Asynchrony (ms)	Cross-correlation difference
Smaller	5.89** \pm 1.52	0.37 \pm 2.62
Larger	20.32** \pm 3.22	9.52** \pm 3.43

Note. *t*-test against null mean = 0 reached significance at ** $p < .05$; * $p < .10$.

musicians' actions are activated in coperformers with whom they must coordinate their actions in time. Duet performances also supported the hypothesis that coperformers simulate each other's actions in order to predict the timing of each other's actions during music performance. We discuss each of these findings in turn.

Action corepresentation

The first goal of the current study was to test the hypothesis that representations of others' actions would be activated during a temporal coordination task in which pianists performed right-hand melodies simultaneously with left-hand accompaniments produced by themselves (bimanual condition) or by another performer (joint condition). The left-hand accompaniment contained either a simple sequence of repetitive pitch changes or a more complex melodic sequence. If representations of the left-hand accompaniment were activated even when it was produced by another performer, the melodic and harmonic complexity of the left-hand accompaniment should have had the same influence on temporal characteristics of the right-hand melody in the joint condition as they did in the bimanual condition. The temporal grouping structure of the right-hand performances matched this prediction: Pianists had a stronger tendency to produce four-beat groups in the right-hand melody when it was performed with a complex left-hand accompaniment than when it was performed with a simple left-hand accompaniment, regardless of whether the accompaniment was produced by the self or another performer. The pianists may have emphasized the

four-beat structure of the melody when the left-hand accompaniment was complex in an attempt to produce more consistent timing in the presence of a more difficult accompaniment. The finding that the left-hand accompaniment had the same influence on the right-hand performance regardless of whether it was produced by oneself or by another performer is consistent with previous findings that an irrelevant stimulus dimension produced similar interference effects when one person was responsible for producing two actions and when two performers were responsible for one action each (Sebanz et al., 2003; Tsai et al., 2006). The current findings thus extend previous evidence of shared representations in turn-taking tasks to a domain that requires simultaneous production of precisely timed independent actions.

We also expected participants' performances to exhibit stronger melody lead (right-hand melody tones produced earlier than left-hand accompaniment tones) and melody tracking (the timing profile of the accompaniment tracking that of the melody) when the melody was accompanied by a simple left-hand part than by a more complex, melodic left-hand part. Performances showed the predicted pattern of melody lead when one participant produced both the melody and the left-hand accompaniment, consistent with previous work (Palmer, 1989, 1996). However, when the left-hand accompaniment was produced by another performer, tones in the left-hand accompaniment were produced earlier than tones in the right-hand melody, inconsistent with the action corepresentation hypothesis. Subsequent analyses showed that the left-hand lead was due to individual differences between the performers in each pair, rather than to characteristics of the left-hand accompaniment. Furthermore, there were no effects of left-hand accompaniment on tracking between the right-hand melody and left-hand accompaniment. Instead, tracking was influenced by whether the accompaniment was produced by oneself or by another performer. Simultaneous timing between hands (high correlations at Lag 0) was evident when one performer controlled both the melody and the accompaniment, consistent with previous work showing that people tend to synchronize

various aspects of their motor output during bimanual coordination, even when the required movements differ between the two hands (Kelso, Putnam, & Goodman, 1983; Kelso, Southard, & Goodman, 1979; Swinnen, Young, Walter, & Serrien, 1991). In contrast, mutual tracking between the right-hand melody and the left-hand accompaniment (high correlations at Lags +1 and -1) was evident when the two parts were produced by different performers. This finding is consistent with previous work showing mutual adaptation between pianists in duet performance, regardless of instructions given to performers concerning who should lead and who should follow (Goebel & Palmer, 2009).

In sum, temporal grouping patterns (analysed within the right-hand melodies) supported the action corepresentation hypothesis that differences between simple and complex left-hand accompaniments would be present regardless of whether the accompaniment was produced by the self or by another performer. In contrast, melody lead (right-hand timing analysed relative to left-hand accompaniment) and melody tracking (temporal influences measured between melody and accompaniment) did not support this hypothesis. Thus, measures specific to the right-hand melody may better reflect the representations of the performer responsible for producing it, whereas measures focusing on the relationship between the right- and left-hand accompaniments show influences of both performers who are responsible for the joint performance.

Action simulation

The second goal of the current study was to examine action simulation during temporal coordination between partners who may adapt to each other's actions. We measured the degree to which pairs of pianists who performed duets together were similar to each other in terms of solo performance rates and showed that the a priori match between partners, rather than the characteristics of either partner alone, influenced coordination in the joint performances. Pairs who were better matched in solo performance were better able to synchronize with each other's

performances and displayed mutual adaptation to each other's timing during joint performances. These findings are consistent with the hypothesis that people should be better able to predict the timing of actions produced by those whose motor systems they can best simulate (Keller et al., 2007; Knoblich & Flach, 2001; Knoblich et al., 2002). Our results thus extend Keller et al.'s findings, in which pianists were better able to synchronize with previously recorded pieces performed by themselves than by another performer, to a task requiring online coordination between mutually adaptive partners.

In contrast to well-matched performers, duet pairs who were less well matched showed larger asynchronies and unidirectional tracking during joint performances. Larger asynchronies between partners with different solo movement rates have been observed in interpersonal coordination of continuous movements such as swinging a pendulum (Amazeen, Schmidt, & Turvey, 1995; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt & Turvey, 1994). In those studies, solo movement rates depended on the physical characteristics (e.g., weight) of the objects with which participants performed a continuous motion, and synchronization differences were attributed to mathematical principles governing coordination between coupled oscillators with different natural frequencies (movement rates). In the current study, pianists' solo performance rates were measured relative to the task goal of performing at the rate set by an initial metronome, rather than spontaneously (without any rate instruction). Thus, explanations based solely on natural frequencies as determined by physical characteristics may contribute to, but not completely explain, the current findings. The implementation of a particular task goal via an initial metronome may also explain the pattern of unidirectional tracking shown by less well-matched pairs. In these pairs, the faster performer tracked the IOIs of the slower performer more so than vice versa. Given that the slower performer's preferred rate was closer to the required metronome rate of 400 ms/IOI in all but one of the pairs, as evidenced in Figure 5, the unidirectional tracking pattern

suggests that slower performers may have constrained their faster partners' preferences in order to meet the task goals.

In sum, the current findings support the hypothesis that partners who are more similar to each other in solo performance should be better able to simulate each other's performances and should therefore be more closely coordinated and better able to adapt to each other's timing during the joint performances. Thus, the current findings are consistent with the hypothesis that people are influenced by properties of their own motor systems when predicting the timing of others' actions.

Conclusions

Duet music performance showed some support for the hypothesis that representations of a copartner's actions are activated during temporal coordination: The melodic and harmonic complexity of the left-hand accompaniment influenced the temporal grouping structure of the right-hand melody in the same way regardless of whether the accompaniment was performed by oneself or by another performer. In contrast, temporal coordination measures, including asynchronies between performers' keystrokes and cross-correlations between performers' timing patterns, revealed influences of individual differences between performers that transcended the complexity of the left-hand accompaniment. Pairs who were better matched before the joint interaction were better synchronized and adapted to each other's timing during the joint interaction, consistent with the hypothesis that performers use properties of their own motor systems to simulate their partners' actions and predict the timing of those actions. Together, these findings indicate that the mechanisms of perception and action that underlie joint actions such as turn taking also support joint music performance, which requires precise temporal coordination between performers.

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