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Pianists duet better when they play with themselves: On the possible role of action simulation in synchronization

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Abstract

Ensemble musicians play in synchrony despite expressively motivated irregularities in timing. We hypothesized that synchrony is achieved by each performer internally simulating the concurrent actions of other ensemble members, relying initially on how they would perform in their stead. Hence, musicians should be better at synchronizing with recordings of their own earlier performances than with others' recordings. We required pianists to record one part from each of several piano duets, and later to play the complementary part in synchrony with their own or others' recordings. The pianists were also asked to identify their own recordings. The pianists were better at synchronizing with their own than with others' performances, and they were able to recognize their own recordings. Furthermore, synchronization accuracy and recognition were correlated: Pianists who were relatively accurate at synchronizing with their own performances were also good at recognizing them. Thus, action simulation may underlie both synchronization and self-recognition.

Keywords: Music; Synchronization; Action simulation; Self-identity; Action identification

1. Introduction

How do musicians playing in an ensemble, such as a piano duo, synchronize their actions with one another? Although the cognitive challenges associated with ensemble performance are manifold (Keller, 2001), one crucial skill for ensemble musicians is the ability to stay in synchrony with one another in spite of the systematic timing irregularities that characterize expressive musical performances (see Rasch, 1988; Repp, 1999; Shaffer, 1984). Hence, the opening question can be rephrased: How does an ensemble musician predict the variable timing of the sounds produced by other ensemble members, to coordinate his or her own sounds with them? The current study investigates the possibility that synchronization in musical ensembles is achieved by

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performers simulating—during ensemble performance—how the accompanying parts might be played (somewhat independently of how they actually are being played). If this is the case, then the simulated parts should bear traces of the performer's own idiosyncratic way of playing, i.e., they should reflect the way in which he or she would perform them. Thus, a musician's actions are steeped in his or her *self-identity*, a term which we use here to refer to procedural knowledge about behavioral consistencies that are used to distinguish one's own actions from those of others. Any evidence in favor of the proposed relationship between action simulation and ensemble synchrony would suggest that music performance may be a novel and fertile domain in which to investigate the role of such self-identity in the cognitive control of interpersonal coordination.

1.1. Action identification

Human individuals have privileged access to their own perceptions and actions. Apart from allowing the individual to regulate his or her behavior, this privilege allows one to recognize the effects of one's own actions as self-generated (Frith, Blakemore, & Wolpert, 2000; Jeannerod, 1999, 2003; Wegner, 2002). It has recently been claimed that self-recognition involves accessing one's own knowledge about how to perform an action (Knoblich & Flach, 2003). This knowledge encompasses all of the movements that an individual has the potential to execute; it relies on the individual's anatomical constraints, learning history, and level of expertise. Thus, during the course of everyday experiences, individuals learn about the peculiar ways in which they do things such as walk, talk, and play the piano.

There are two main sources of experimental evidence supporting the assumption that action identification relies on an individual's action knowledge. First, it has been shown that people are more accurate at predicting the location and timing of forthcoming events for their own actions than for others' actions (Flach, Knoblich, & Prinz, 2003, 2004; Knoblich & Flach, 2001; Knoblich, Seigerschmidt, Flach, & Prinz, 2002). Second, studies of diverse behaviors including handwriting, body movements, clapping, and piano playing have demonstrated that individuals are able to distinguish between recordings of actions performed by themselves and recordings of actions performed by others (Flach, Knoblich, & Prinz, 2004; Grèzes, Frith, & Passingham, 2004; Knoblich & Prinz, 2001; Loula, Prasad, Harber, & Shiffrar, 2005; Repp, 1987; Repp & Knoblich, 2004). Importantly, actions were recognized as self-generated even when the recordings were edited to remove salient cues that may facilitate easy identification. For example, Repp and Knoblich (2004) found that expert pianists were able to recognize their own performances equally well in the original recordings and in recordings that were normalized in terms of tempo (overall rate) and dynamics (changes in loudness). Notably, these authors also found that pianists were able to recognize their own performances even when they had not heard any sound during the recording session, which suggests that episodic memory cannot provide a full explanation of how self-generated actions were recognized.

1.2. Action simulation

We hypothesize that to recognize an earlier action as self-generated, or to predict action-related effects accurately, individuals access their action knowledge by internally simulating the action. This process of simulation involves imagining—in anticipation—the movements and effects that characterize the event, and it is triggered automatically when an action is observed (Dokic & Proust, 2002; Jeannerod, 2003; Knoblich & Flach, 2003). Thus, the notion of action simulation presupposes close links between perception and action. In fairly direct support of action simulation, research in neuroscience has revealed brain areas—e.g., the so-called 'mirror neuron' system in the pre-motor cortex—that are active not only when carrying out a goal-directed movement, but also when simply observing somebody else performing the movement (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti & Craighero, 2004; Rizzolatti, Fogassi, & Gallese, 2001).

Research on action identification suggests that, once the observation of a recording of an action triggers its simulation, the degree of discrepancy between the simulated and the observed action determines whether the action is attributed to self or other, and whether or not accurate predictions can be generated about forthcoming events. The match between simulation and observation is better in the case of self-generated actions than for other-generated actions because in the former the simulation is carried out by the same system—with all its idiosyncratic constraints—that produced the observed action. In other words, the action system resonates most strongly with signals that it produced earlier (Knoblich & Flach, 2003). If this is true, action simulation might lead to more accurate temporal predictions when one coordinates a new action with an observed action one has performed previously than when one must coordinate with somebody else's earlier action. We tested this prediction in the music domain.

1.3. The current study

The aim of the current study was to investigate the role of action simulation in synchronization during musical ensemble performance. Skilled pianists were required to record one part (or, in some cases, both parts separately) from several piano duets. The pianists returned at a later date to play the complementary part in synchrony with either their own recording or other participants' recordings. The pianists were also asked to identify which recordings were their own. Thus, we examined both the accuracy of temporal predictions—a prerequisite for synchronization—and the recognition of self-generated actions in a task that involved skilled musicians performing real music. Our exclusive focus on the auditory channel was motivated by a couple of considerations. First, although visual cues may be important for synchronization at points when musicians must start playing together after a relatively long silent gap (or when in large groups), visual information is likely to be much less important during continuous playing. Second, even if we had used video images in which the identity of the recorded duet partner was disguised, the live pianist would have had difficulty viewing these images while reading the score.

We expected to find that the pianists can recognize their own performances at levels well above chance (replicating the results of Repp & Knoblich, 2004). Furthermore, we expected that the pianists would be better at synchronizing with recordings of their own earlier performances than with recordings of others. Finally, if action simulation subserves both temporal prediction and action identification, then we should observe a correlation between synchronization and recognition: Pianists who are relatively good at synchronizing with their own performances should also be good at recognizing them.

A possible alternative to the action simulation account is that superior synchronization accuracy with self-produced performances follows simply from individual pianists playing in the way they do. On this account, a better temporal match is to be expected a priori when pianists play a duet with themselves because their own playing is in general more similar to their own recorded playing than to other pianists' recorded playing. We tested this 'self-similarity' hypothesis by measuring the degree of correlation between event timing in the two parts of the duets when both parts were recorded (separately) by the same pianist or by different pianists. Observing a self-advantage (i.e., stronger correlations when both parts were recorded by the same pianist) under such conditions would suggest that the self-similarity account is a viable alternative to the action simulation account. We should note that such an advantage is by no means obvious because the two parts of a duet are usually complementary rather than similar to each other.

2. Methods

2.1. Participants

Nine skilled pianists (3 men, 6 women) participated as paid volunteers. Six of them were graduate students at the Yale School of Music. Three were undergraduate students in Yale College (two juniors and one sophomore) who were taking lessons with members of the Music School faculty. Three groups of three pianists each (A, B, C) were formed, with the undergraduates constituting Group C.

2.2. Materials and design

Excerpts constituting the beginnings of three pieces were selected from the piano duet (one piano, four hands) literature: No. 1 (Moderato) in D major (Bars 1–35) and No. 3 (Adagio) in F major (Bars 1–25) from Carl Maria von Weber's *Huit Pièces* (*Eight Pieces*), op. 60, and No. 1 (Adagio cantabile) in A-flat major (Bars 1–24) from Edvard Grieg's *Symphonic Pieces*, op. 14. They will be referred to in the following as W1, W3, and G1, respectively, with P (for *primo* or upper part) or S (for *secondo* or lower part) appended when appropriate.

G1 consisted of a simple melody (P) with an elaborate accompaniment (S), whereas in W1 and W3 the two parts were on a more equal footing and shared the thematic material.

Suggested metronome settings were added to the scores by author BHR (an experienced amateur pianist). At these tempi, the playing durations were about 70 s (W1), 66 s (W2), and 98 s (G1). Because sessions would have lasted too long if every pianist had played every part, the three pieces were assigned to the three groups such that each group played P of one piece, S of another piece, and both P and S of the third piece (see Table 1).

2.3. *Equipment and procedure*

Participants came for two sessions, 2–3 months apart. During Session I, each pianist recorded the four assigned parts. During Session II, each pianist was recorded playing duets with the recorded parts. The instrument was a Yamaha Clavinova CLP-11 digital piano whose sound was heard over earphones. Recording and playback were controlled via a MIDI translator by a Macintosh iMac G4 computer using MAX 4.0.9 software. In Session II, the recorded part was played back on the Clavinova while the pianist was recorded playing on the same instrument.

2.3.1. *Session I*

Each pianist played the four assigned parts in the order indicated in Table 1. All participants said that they were totally unfamiliar with all three pieces. For each piece, the pianist set the built-in metronome of the Clavinova to the suggested setting. He or she then practiced the music until he or she felt comfortable playing it. The metronome was then turned off, and the pianist was recorded playing the excerpt. If the pianist was dissatisfied with his or her playing, the recording was repeated.

2.3.2. *Preparation of materials for Session II*

To identify any serious errors in the recorded materials, author BHR listened to all 36 recordings and also played in duet with each of them. Several gross timing errors that seriously disrupted the coordination in duet playing were identified. One pianist changed the tempo halfway through W3S; another played G1P much faster than suggested. These errors were corrected by rescaling the tempo appropriately in the MIDI files. In addition, seven instances of excessive lengthening or shortening of a long note or rest were detected, and these were corrected by adding or subtracting an appropriate amount of time in the MIDI files, according to author BHR's judgment. (Five of these excessive timing distortions were committed by pianist C1, who we later excluded from our primary analyses—see below.) In addition, BHR himself recorded all parts, playing with the metronome on. These fairly rigidly timed performances were used for duet practice in Session II. Each recorded performance was prefixed with lead-in beats to give duet players an indication of when to start playing the other part.

2.3.3. *Session II*

Pianists were informed that they would have to play duets both with their own recordings and with those of two other unnamed pianists (those in the same group). This involved playing the complementary parts (two of which the pianists had not encountered previously; see Table 1) in synchrony with the four recorded parts. The order in which the four recorded parts were presented to the three pianists in each group was varied and

Table 1
Assignment of parts to the three groups of pianists

	W1P	W1S	W3P	W3S	G1P	G1S
Group A	1		3	4		2
Group B		2	1		3	4
Group C	3	4		2	1	

Digits indicate the order in which the parts were performed.

Fig. 1. The first four bars of W1 (where the arrows indicate nominally simultaneous notes between the primo and secondo parts).

approximately counterbalanced across all nine pianists. The order of the three recordings of each part was also varied across the three pianists in each group.

The scores of both parts of each piece were placed on the music stand, side by side. Pianists first practiced playing their assigned part in duet with BHR's recorded performance of the other part, until they felt comfortable. Then they were recorded playing the duet with each of the recordings made by the three pianists in their group. The pianists were instructed to strive for the degree of synchronization accuracy that is required in normal instances of ensemble playing. The duet performance with each recording was repeated twice (i.e., three takes) before proceeding to the next recording. After having played in duet with all three recordings of a given part, the pianist was asked to make a forced-choice guess as to which of the three recordings had been his or her own. The same procedure was followed with the remaining three assigned parts, resulting in a total of 9 (pianists) × 4 (parts) × 3 (recordings) × 3 (takes) = 324 duet performances to be analyzed.

2.4. Data analysis

We examined the musical scores of the P and S parts of each piece and marked all notes that were nominally simultaneous between the two parts ("critical notes"; see Fig. 1 for an example). If there were several simultaneous critical notes in the same part, only the one with the highest pitch was considered. The number of critical note pairs was 114 for W1, 64 for W3, and 72 for G1, and they were distributed irregularly across various metrical score positions.

Using a spreadsheet program, the critical pitches were identified, marked, and extracted together with their note onset times from the MIDI data. The data extracted from the Session II performances were aligned with those extracted from the recorded part that the duet was played with, and asynchronies between the respective onset times were computed by subtracting onset times in the recorded parts from those in the parts that were performed 'live.' This conventional method of computing asynchronies results in negative asynchronies when the pianist plays ahead of the recorded part.

3. Results

3.1. Recognition of self-produced performances

Recognition accuracy was examined by first calculating the proportion of correct self-identifications by each pianist ($M = 0.58$; chance = 0.33), and then converting these proportions to d-prime scores (see Macmillan & Creelman, 1991). In the present context, d-prime scores reflect pianists' sensitivity to differences between their own performances and others' performances. Mean d-prime was 1.06 ($SD = 1.17$), which a t test revealed to be significantly different from zero, $t(8) = 2.67$, $p < .05$. This result indicates that pianists were able to recognize their own performances at levels reliably better than chance.

3.2. Synchronization with self vs. other

Before analyzing self/other differences in synchronization accuracy, we assessed participants' overall synchronization accuracy by calculating the average standard deviation of asynchronies for each participant. One participant (C1, who after the experiment had spontaneously declared herself inexperienced at ensemble playing) had a value (71 ms) that was more than two standard deviations above the mean standard deviation of asynchronies for the sample ($M = 62$ ms, $SD = 4$ ms). Because of this relatively poor overall synchronization performance, we decided to exclude the data of this participant from further analysis.

For the remaining participants, large asynchronies (exceeding ±100 ms) were removed before conducting further analyses. Most of these large asynchronies were due to pianists' difficulties in predicting the timing of Session I performances following long notes or rests, in part because longer intervals imply greater temporal uncertainty and in part because these long notes and rests had already been rendered inaccurately in Session I. We felt that these large asynchronies, which would have dominated the results, should be considered timing errors and be separated from the more detailed level of coordination we were interested in. This filtering amounted to 8.4% of all asynchronies.

Three measures were obtained from each filtered series of asynchronies: The median, the median of absolute values, and the standard deviation. Data pertaining to each of these measures were averaged across pieces/parts and across performances with other recorded partners, and were then subjected to separate 2×3 analyses of variance (ANOVAs) with the variables of partner (self or other) and take (1, 2, or 3). The Greenhouse-Geisser correction was applied when the value of the degrees of freedom in the numerator exceeded one.

The median asynchrony provides an indication of a tendency to lead or lag the recorded performance when playing a duet. The ANOVA on median asynchrony (-1.2 ms, $SD = 6.2$ ms) revealed that it was not affected reliably by partner, take, or their interaction, $ps > .5$. Furthermore, a t test revealed that median asynchrony was not significantly different from zero, $t(7) = -.53$, n.s., indicating an absence of the general tendency to lead that is often observed in studies of synchronization with simple isochronous pacing signals (see Aschersleben, 2002).

Fig. 2 displays averages for the median absolute value of asynchrony and the standard deviation of asynchronies, which are commonly used measures of synchronization accuracy. The absolute value of asynchrony and the standard deviation of asynchronies were both lower when pianists were playing with their own recorded performances than with others' performances. The reliability of these findings was confirmed by main effects of partner in the ANOVAs on absolute asynchrony, $F(1,7) = 14.21, p < .01$, and the standard deviation of asynchronies, $F(1,7) = 10.55$, $p < .02$.[1] Thus, errors in synchronization were smaller and less variable with self-produced than with other-produced performances. There were no significant interactions when piece (W1, W3, or G1) was included as a variable in the analyses.

The ANOVAs on these data also revealed main effects of the take factor for absolute asynchrony, $F(2,14) = 10.06$, $p < .01$, and the standard deviation of asynchronies, $F(2,14) = 6.89$, $p < .01$. As can be seen in Fig. 2, absolute asynchrony and the standard deviation of asynchronies both decrease from take 1 to take 2, and then seem to plateau. This suggests that pianists' abilities to anticipate upcoming events in the recorded parts did not improve beyond take 2. The above pattern of results is qualitatively similar for synchronization with self-produced and other-produced performances, as indicated by the lack of a significant interaction between partner and take for absolute asynchrony, $F(2,14) = 1.94$, $p > .20$, and the standard deviation of asynchronies, $F(2,14) = 0.25$. These findings suggest that the advantages of synchronizing with one's own performances did not abate with practice.

To assess whether the observed self-advantage in synchronization could be due merely to self-similarity in playing technique, we estimated the degree of correlation between event timing in performances of the primo and secondo parts of the same piece as recorded by either the same pianist or different pianists in the first experimental session. (Pianists in each group recorded both parts for a different one of the three pieces; see Table 1.) The time series that were thus compared comprised the normalized inter-onset intervals between the critical notes in the recorded primo and secondo parts of each piece. The normalization procedure entailed

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[1] These effects were still significant when participant C1 was included in the analyses.

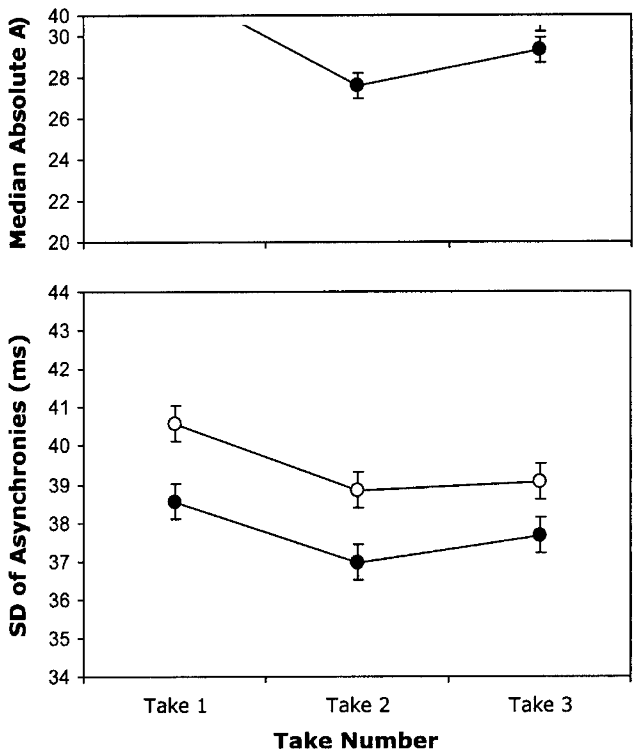

Fig. 2. The median absolute value of asynchronies (top panel) and the standard deviation of asynchronies (bottom panel) for synchronization with self-produced and other-produced recordings across takes 1, 2, and 3. The error bars represent standard error.

dividing the raw inter-onset intervals by the number of smallest note values they contained.[2] The number of smallest note values per interval depended on the nominal interval duration in the score, and the smallest note values were 16th notes in W1 and G1, and 32nd notes in W3. A pairwise t test revealed that the difference in the strength of correlation between same-pianist pairings (average $r = .54$) and pairings of each pianist with other pianists within the same group (average $r = .45$) was not reliable, $t(7) = 1.87$, $p > .1$ (correlation coefficients were converted to Fisher z' scores prior to analysis). Thus, self-similarity alone does not appear to be responsible for the self-advantage in synchronization. The moderately high positive correlations reflect the structural commonality of the two parts of the same piece.

3.3. Dependencies between recognition and synchronization accuracy

To examine the relationship between recognizing self-generated actions and synchronization, we computed correlation coefficients between recognition accuracy scores and self/other difference scores based on each of our two measures of synchronization accuracy. These difference scores were calculated—separately for the

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[2] Without this normalization, the correlation would simply have reflected the correspondence of long and short intervals in the two parts. The normalized intervals reflect the relative lengthening and shortening of intervals due to expressive timing, although the analysis is admittedly coarse because of the irregular and often wide spacing of critical notes.

absolute value of asynchrony and the standard deviation of asynchrony—by subtracting each pianist's average value for synchronization with self-produced recordings from his or her average value for synchronization with other-produced recordings. Recognition accuracy was positively correlated with self/other differences in the standard deviation of asynchronies ($r = .75, p < .05$), and the correlation between recognition accuracy and self/other differences in absolute asynchrony approached significance ($r = .65$, $p = .08$). Thus, we found some evidence that pianists who were relatively good at synchronizing with their own performances were also good at recognizing them.

4. Discussion

In this study, we investigated synchronization in musical ensembles by requiring skilled pianists first to record one part from several unfamiliar duets, and then to play the complementary part in time with either their own or others' recordings after a delay of several months. The results indicate that the pianists were not only able to recognize their own recordings reliably, but they were also better at synchronizing with their own performances than with others' performances. Furthermore, synchronization accuracy and recognition were found to be related to one another: The larger the advantage a pianist enjoyed when synchronizing with self-produced performances, the better he or she was at identifying them.

These findings support our hypothesis that ensemble musicians maintain synchrony during expressively timed performances by simulating the concurrent actions of other ensemble members. By thus imagining how other parts might be played, in anticipation of how they are actually played, musicians are able to make temporal predictions about when to act to be in synchrony. In line with previous work on action identification (see Knoblich & Flach, 2003), we assume that in our experiment these action simulations matched best with how the parts were actually played in the case of self-generated performances because in this situation the system doing the simulating did the generating. Here, we propose that this good fit between simulated and observed actions both (1) ensured that the temporal predictions underlying synchronization were more accurate when playing along with one's own recordings than with others' recordings and (2) allowed pianists to recognize their own earlier performances. Thus, the same process of action simulation seems to underlie both synchronization and the recognition of self-generated actions.

Although factors that are not necessarily related to action simulation could have contributed to our findings, we believe that none of them provides an adequate alternative explanation. Perhaps the most obvious such consideration is the degree to which episodic memory for the specific movements and sounds experienced during the first experimental session contributed to self-recognition and the self-advantage in synchronization during the second session. It is unlikely that episodic memory for sound is fully accountable because previous work has demonstrated that pianists can recognize recordings of their own performances regardless of whether or not they hear sound during the recording session (Repp & Knoblich, 2004). Furthermore, it seems implausible that episodic memories for subtle performance details would be able to survive the interval of several months that separated the sessions, during which time the pianists went about their business of playing different repertoire for countless hours.

It also seems unlikely that the self-advantage in synchronization can be attributed solely to self-similarity in performance technique because we found little evidence for differences in the temporal match between events in primo and secondo parts based on whether they were recorded (separately) by the same pianist or by different pianists.

In addition, the possibility that the self-synchronization advantage derives solely from especially efficient (auditory) perceptual processing is untenable because sensorimotor synchronization requires the timing of future events to be anticipated in the motor system. For a pianist to depress a key in synchrony with an external event, the finger must begin its descent several tens of milliseconds before the event's actual onset. Note that we are not claiming that pure perceptual or pure motor processes make no contribution to the self-synchronization advantage. Rather, we argue that pure perceptual or motor processes are alone not up to the task of explaining our observations. This leads us to claim that perceptual and motor processes coalesce during simulation in such a way that when the duet performer imagines upcoming events in the other part—to synchronize with them—this imagined music is flavored by the performer's own action style.

Another consideration is whether the observed relationship between self-recognition and the self-advantage in synchronization really implies that both are directly underscored by the same mechanism of action simulation. Because the recognition judgments were made after the duet playing, a plausible alternative is that rel- a secondary task with incompatible movement timing demands (Flach et al., 2004). Thus, the results of previous research suggest that self-recognition is based directly on an internal simulation process that is triggered automatically by external action observation. Our results suggest that action simulation also underlies synchronization. The present study therefore extends previous research by presenting evidence that simulation plays a role in coordinating one's overt actions with those of another, as well as in perceiving others' actions.

We readily acknowledge that the action simulation carried out by the pianists during duet performance was most likely fragmentary and intermittent, because the pianists did not have enough time to learn the unfamiliar parts well.[3] It is the more remarkable, then, that we did find a significant effect of partner identity (self vs. other) in our study. We would expect to find a larger self-other difference with duets that are thoroughly familiar to the pianists. Indeed, if pianists were asked to play in unison with familiar solo pieces recorded by themselves and others, a self-other difference would be so obvious as to be almost trivial. Our present study avoided such triviality by focusing on a situation in which the recorded and played parts are quite different from each other and relatively unfamiliar.

To conclude, the current findings suggest that musicians maintain synchrony with one another during ensemble performance by simulating each others' actions. When these action simulations match closely with how the other parts are actually played (as when pianists play along with their own recordings), the performer is able to anticipate the expressively-motivated timing irregularities produced by the other ensemble member(s). Thus, synchronization accuracy is determined by the degree to which the action styles of the performers are compatible, with higher compatibility leading to tighter perception-action coupling and hence better synchronization. This invites speculation that the compatibility between performers' action styles may be a predictor of an ensemble's quality, although the possibility that musicians learn their partners' action styles should be acknowledged. To pose a testable question: Do pianists with similar action styles (measured independently during solo performance) perform duets better than pianists with less similar action styles? Our findings suggest that this should be expected not merely on the basis of self-similarity in performance technique, but rather because such similarity facilitates the accurate simulation of other musicians' actions. More generally, action simulation presumably mediates synchronization in other instances of 'joint action' (Clark, 1996; Knoblich & Jordan, 2003) that require precise temporal coordination, such as dancing and team sports. In short, simulation may be the medium in which perception and action coexist. We believe that the study of duet performance is a promising domain for further research into the role of self-identity and self-similarity in interpersonal action coordination.

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References

Aschersleben, G. (2002). Temporal control of movements in sensorimotor synchronization. *Brain and Cognition, 48*, 66–79.

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[3] Imperfect knowledge and lack of memorization of their own part also prevented pianists from focusing on the score of the recorded part during duet playing, although it was on the music stand.

Clark, H. H. (1996). *Using language*. Cambridge: Cambridge University Press.

Dokic, J., & Proust, J. (2002). *Simulation and knowledge of action*. Amsterdam: John Benjamins.

Flach, R., Knoblich, G., & Prinz, W. (2003). Off-line authorship effects in action perception. *Brain and Cognition, 53*, 503–513.

Flach, R., Knoblich, G., & Prinz, W. (2004). Recognizing one's own clapping: The role of temporal cues in self-recognition. *Psychological Research, 69*, 147–156.

Frith, C. D., Blakemore, S.-J., & Wolpert, D. M. (2000). Abnormalities in the awareness and control of action. *Philosophical Transactions of the Royal Society London B, 355*, 1771–1788.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain, 119*, 593–609.

Grèzes, J., Frith, C. D., & Passingham, R. E. (2004). Inferring false beliefs from the actions of oneself and others: An fMRI study. *NeuroImage, 21*, 744–750.

Jeannerod, M. (1999). The 25th Bartlett Lecture: To act or not to act: Perspectives on the representation of actions. *Quarterly Journal of Experimental Psychology, 52A*, 1–29.

Jeannerod, M. (2003). The mechanism of self-recognition in humans. *Behavioral Brain Research, 142*, 1–15.

Keller, P. E. (2001). Attentional resource allocation in musical ensemble performance. *Psychology of Music, 29*, 20–38.

Knoblich, G., & Flach, R. (2001). Predicting the effects of actions: Interactions of perception and action. *Psychological Science, 12*, 467–472.

Knoblich, G., & Flach, R. (2003). Action identity: Evidence from self-recognition, prediction, and coordination. *Consciousness and Cognition, 12*, 620–632.

Knoblich, G., & Jordan, J. S. (2003). Action coordination in groups and individuals: Learning anticipatory control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 1006–1016.

Knoblich, G., & Prinz, W. (2001). Recognition of self-generated actions from kinematic displays of drawing. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 456–465.

Knoblich, G., Seigerschmidt, E., Flach, R., & Prinz, W. (2002). Authorship effects in the prediction of handwriting strokes: Evidence for action simulation during action perception. *Quarterly Journal of Experimental Psychology, 55A*, 1027–1046.

Loula, F., Prasad, S., Harber, K., & Shiffrar, M. (2005). Recognizing people from their movements. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 210–220.

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. Cambridge: Cambridge University Press.

Rasch, R. A. (1988). Timing and synchronization in ensemble performance. In J. A. Sloboda (Ed.), *Generative processes in music: The psychology of performance, improvisation, and composition* (pp. 70–90). Clarendon Press: Oxford.

Repp, B. H. (1987). The sound of two hands clapping: An exploratory study. *Journal of the Acoustical Society of America, 81*, 1100–1109.

Repp, B. H. (1999). Relationships between performance timing, perception of timing perturbations, and perceptual-motor synchronisation in two Chopin preludes. *Australian Journal of Psychology, 51*, 188–203.

Repp, B. H., & Knoblich, G. (2004). Perceiving action identity: How pianists recognize their own performances. *Psychological Science, 15*, 604–609.

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience, 27*, 169–192.

Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying imitation and the understanding of action. *Nature Reviews Neuroscience, 2*, 661–670.

Shaffer, L. H. (1984). Timing in solo and duet piano performances. *Quarterly Journal of Experimental Psychology, 36A*, 577–595.

Wegner, D. M. (2002). *The illusion of conscious will*. Cambridge, MA: MIT Press.