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RESEARCH ARTICLE

# The role of temporal prediction abilities in interpersonal sensorimotor synchronization

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**Abstract** Musical ensemble performance is a form of joint action that requires highly precise yet flexible interpersonal action coordination. To maintain synchrony during expressive passages that contain tempo variations, musicians presumably anticipate the sounds that will be produced by their co-performers. Our previous studies revealed that individuals differ in their ability to predict upcoming event timing when finger tapping in synchrony with tempo-changing pacing signals (i.e., the degree to which inter-tap intervals match vs. lag behind inter-onset intervals in the pacing signal varies between individuals). The current study examines the influence of these individual differences on synchronization performance in a dyadic tapping task. In addition, the stability of individual prediction tendencies across time is tested. Individuals with high or low prediction tendencies were invited to participate in two experimental sessions. In both sessions, participants were asked (1) to tap alone with a tempo-changing pacing signal and (2) to tap synchronously in dyads comprising individuals with similar or different prediction tendencies. Results indicated that individual differences in prediction tendencies were stable over several months and played a significant role in dyadic synchronization. Dyads composed of two high-predicting individuals tapped with higher accuracy and less variability than low-predicting dyads, while mixed dyads were intermediate. Prediction tendencies explained variance in dyadic synchronization performance over and above individual synchronization ability. These findings suggest that individual differences in temporal prediction ability may potentially mediate the interaction of cognitive, motor, and social processes underlying musical joint action.

**Keywords** Sensorimotor synchronization · Dyadic finger tapping · Temporal prediction · Joint action

## Introduction

Musical ensemble performance is a complex affair involving the interaction of cognitive, motor, and social processes. The most basic requirement is interpersonal action coordination. To create a cohesive soundscape and thus the impression of a coherent piece of music, the members of an ensemble must coordinate their movements in order to produce sounds that complement each other. The temporal attunement that is at the heart of this process requires individual actions to be both highly precise and flexible. Competent musicians are able to accomplish such temporal action coordination with remarkable facility. Sounds produced by different instrumental voices that are nominally synchronous according to the notated score are typically played with small asynchronies with a spread of only around 30–50 ms, even during expressive passages that are characterized by considerable deviations from isochronous tempo (Clynes and Walker 1986; Keller and Appel 2010; Rasch 1979; Shaffer 1984). These asynchronies are much smaller than what would be expected if musicians were predominantly reacting to the perceived sounds or observed actions of their co-performers or a conductor. This suggests that musicians rely on *anticipatory* mechanisms in order to achieve good synchrony. In other words, they predict the sounds that will be produced

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by their co-performers and coordinate their own anticipated actions with these predictions (see Keller 2008).

To date, the perceptual, behavioral, and neural mechanisms underlying interpersonal action coordination in music-related contexts are only partially understood despite steadily growing research interest in joint music production (e.g., Goebl and Palmer 2009; Keller and Appel 2010; Keller et al. 2007; Lindenberger et al. 2009). One promising approach to study the basic time-keeping processes involved in musical joint action is provided by sensorimotor synchronization (SMS) paradigms that require an individual to tap a finger in time with simple auditory sequences. Despite the reduced demands of these tasks, they are relevant to more complex musical activities, as the ability to coordinate one's behavior with simple rhythmic sequences can be considered a prerequisite for all joint music-related behavior (Merker et al. 2009).

Related studies that require participants to tap along with recordings of expressively performed music have shown that individuals can synchronize accurately with the local tempo variations in these performances (e.g., Dixon et al. 2006; Rankin et al. 2009). Work along these lines has revealed that there were also strong lag-0 cross-correlations (CCs) between the individuals' inter-tap intervals (ITIs) and the inter-onset intervals (IOIs) of the corresponding tones in the musical sequences (Repp 1999, 2002). Such high lag-0 CCs (relative to lag-1 CCs) reflect the fact that individuals adjusted their ITIs more strongly on the basis of *upcoming* rather than preceding IOIs in the music: in other words, they were able to anticipate or predict ongoing timing variations, at least after some experience with the musical piece (Repp 2002).

In contrast, relatively large lag-1 CCs were found when participants were asked to tap along with an expressively timed sequence of simple clicks whose IOIs varied according to the expressive timing pattern of a complex piece of music (though this was unknown to the participants). This indicates that individuals *tracked* the timing variations of the sequence at a lag of one event (Repp 2002, 2006). Similar tracking behavior has been observed for SMS with randomly perturbed or regularly modulated deviations at subliminal or just supraliminal detection levels (e.g., Madison and Merker 2005; Thaut et al. 1998). However, when timing variations in the auditory sequence were easily detectable and followed a regular or familiar pattern, participants' ITIs tended to match the sequence timing without a time lag (see Michon 1967; Rankin et al. 2009; Repp 2005).

Two of our previous studies have also focused on anticipation during SMS (Pecenka and Keller 2009a, b). Both studies investigated individuals' temporal prediction abilities during on-beat finger tapping to a tempo-changing pacing signal. Tempo transitions were designed to resemble tempo variations found in music. The ratio of lag-0 over lag-1 CCs between ITIs and the IOIs of the pacing signal was computed relative to the lag-1 auto-correlation of the sequence to assess the degree to which individuals predicted upcoming tempo changes (cf. Repp 2002). Prediction indices in these participant samples, which comprised mostly amateur musicians, indicated that about two-thirds of the individuals mainly predicted (ratio $> 1$) ongoing tempo changes. The remaining individuals showed weaker prediction (ratio $< 1$; i.e., they in fact displayed a tendency to track the changes). However, as both studies required individuals to tap along with an expressively timed, but non-reactive pacing signal, results are not fully informative about the role of individual differences in prediction abilities in ensemble coordination.

One strategy for uncovering the cognitive/motor and social processes underlying musical joint action is to identify stable individual differences that predict which combinations of performers will be especially good at synchronizing with one another. Although a handful of studies have investigated SMS between two individuals co-acting in real time (e.g., Kirschner and Tomasello 2009; Kleinspehn 2008; Konvalinka et al. 2010; Merker et al. 2009; Nowicki 2009), the majority were not concerned with characteristics of the individuals that benefit interpersonal action coordination. A related study in the music domain did, however, reveal a relationship between individual differences in three ensemble-relevant 'skills' (pertaining to anticipatory mechanisms, adaptive error correction processes, and divided attention) and interpersonal coordination during duet piano performance (Keller 2008).

Above all, joint music making is an inherently social activity. To date, a few studies have investigated social implications of musical or basic rhythmical interactions. Joint music making and acting in synchrony (e.g., joint finger tapping) have been shown to boost prosocial behavior, cooperation, and feelings of affiliation between interaction partners (e.g., Hove and Risen 2009; Kirschner and Tomasello 2010; Wiltermuth and Heath 2009). There is also evidence that social competence can modulate performance on interpersonal coordination tasks, such as drumming and hand-held pendulum swinging (Kleinspehn 2008; Schmidt et al. 1994). Such relationships between social factors and temporal coordination abilities are presumably grounded in basic cognitive/motor mechanisms that are honed through an individual's life experiences.

The aim of the present study is to investigate individual differences in basic prediction tendencies and their influence on synchronization performance in a dyadic finger tapping task. To this end, we set up differently configured pairs of individuals (most of whom were musicians) to allow systematic examination of the impact of different individual abilities on dyadic performance. We hypothesize that pairs comprising two high-predicting individuals will show superior performance in dyadic synchronization compared to low-predicting pairs. We also test whether this benefit on dyadic synchronization extends beyond that which would be expected on the basis of each individual's synchronization ability. Furthermore, we are interested in whether joint synchronization performance of mixed pairs will be intermediate to high- and low-predicting pairs, or whether dyadic performance will be influenced disproportionately by one of the ensemble members.

A subsidiary aim of the current study is to examine the stability of individual prediction tendencies across time. Before investigating the explanatory power of prediction tendencies for dyadic performance, it is necessary to verify that individual differences in prediction abilities are a reliable characteristic of individual SMS performance.

## Methods

### Participants

Forty-four individuals who displayed prediction tendencies that were high (ratio $> 1$; $n = 23$; *range* $= 1.01$–$1.13$; $M = 1.07$; $SD = 0.03$) or low (ratio $< 1$; $n = 21$; *range* $= 0.88$–$0.99$; $M = 0.96$; $SD = 0.03$) in previous studies participated in the current experiment. These individuals will be referred to as high predictors (HPs) and low predictors (LPs).[1]

The HP's mean age was 24.7 years ($SD = 3.1$), and 12 were female. Most were amateur musicians ($n = 13$) or professional musicians ($n = 9$) with varying amounts of experience (years of instrument playing/singing summed over all instruments: *range* $= 15$–$40$, $M = 27.7$, $SD = 7.2$). One HP was a non-musician. The LP's mean age was 23.9 years ($SD = 2.5$), and 11 were female. They included amateur musicians ($n = 14$) and professional musicians ($n = 3$) with varying amounts of experience (*range* $=$ 6–40, $M = 18.5$, $SD = 10.0$). Four LPs were non-musicians.

### Tasks and materials

The selection of participants for the current experiment was based on participants' prediction indices assessed on a previous occasion. These measures were completed up to 2 years prior to the current study (in days: $M = 325$, $SD = 213$). The current experiment was run across two sessions on separate days up to 3 months apart (in days: $M = 16$, $SD = 24$). In both sessions, participants were first asked to tap alone in synchrony with a tempo-changing pacing signal, and afterward tapped in dyads with another person. Figure 1 provides an overview of the general assessment protocol.

#### *Solo tapping*

*Task and procedure* A solo tapping task was completed prior to dyadic tapping in the congruent (C) and mixed (M) sessions. The individual participant was seated in a quiet laboratory room and was instructed to tap a finger on a drum pad in synchrony with tempo-changing pacing signals presented over headphones. After short practice, the participant completed either 10 (C) or 12 (M) tapping trials. Average trial duration was 36 s. The solo tapping task took 8–10 min.

*Materials and apparatus* Tempo changes in the pacing signal resembled tempo variations found in performed music (i.e., accelerando and ritardando). In session C, each trial consisted of 78 identical pacing sounds and contained 12 continuous tempo changes spanning a range corresponding to 400–500 ms IOIs. Tempo changes proceeded over 7 beats, following a sinusoidal function. These sequences were identical to those used in our previous study (Pecenka and Keller 2009b). Tempo changes in session M were more variable; they proceeded over 5–11 beats following quadratic functions. Each trial consisted of 70–76 identical pacing sounds and contained 9 or 10

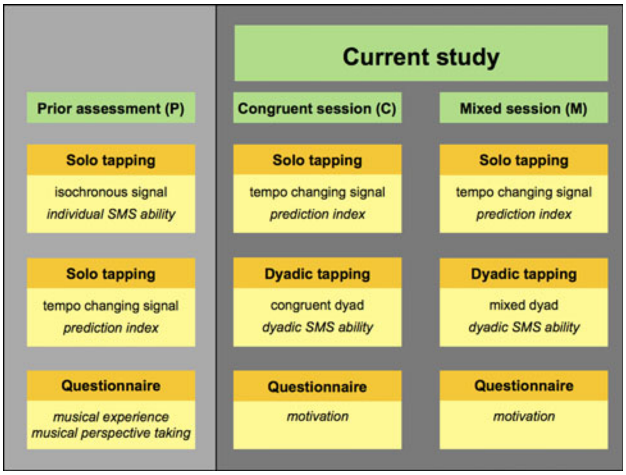

**Fig. 1** Assessment protocol of the current study and a prior test session. The prior assessment yielded prediction indices that were used for dyad composition in the current study. The order of the congruent and mixed sessions was counterbalanced. Within each session, tasks were completed from *top* to *bottom*. Variables used in later analyses are printed in italics

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[1] We assigned participants to one of the two groups in order to manipulate dyad composition experimentally (with respect to individual prediction abilities) and to test its effect on dyadic SMS performance. Note, however, that prediction tendencies exist on a continuum and are approximately normally distributed.

continuous tempo changes spanning a range corresponding to 400–600 ms IOIs.

Different technical setups were used for the tasks in sessions C and M, and the sessions were run in different laboratory rooms. Both tasks and setups had already been used in previous studies and were held constant to allow for later comparisons between studies. In session C, participants tapped on a MIDI drum pad (Roland SPD-6) connected to the MIDI sound card (Creative SB Audigy ZS) of a computer running MaxMSP 5.0 software under Windows XP Professional. MaxMSP sent signals to a Roland SPD-S drum pad, which generated pacing sounds articulated by a sampled bell sound. Sounds were presented over Sennheiser headphones (HD 280 Professional). Finger taps did not trigger sounds.

In session M, participants tapped on a MIDI drum pad (Roland Handsonic HPD-10) connected via a MIDI interface (MOTU timepiece MTP AV) to a Macintosh computer running MaxMSP. The MIDI output of MaxMSP sent signals to a synthesizer (Yamaha MOTIF-RACK ES), which generated a tempo-changing pacing signal featuring a clarinet sound (330 Hz, 100 ms duration) presented over headphones. Finger taps did not trigger sounds.

### *Dyadic tapping*

*Dyad composition* The composition of the dyads in the current study was varied systematically between the two experimental sessions. In session C, individuals with similar prediction tendencies were paired (HP + HP; LP + LP); in session M, individuals with different prediction tendencies were paired (HP + LP). Due to dyadic misassignment, two participants completed an additional third session, and one participant was tested twice in a mixed dyad only. Two participants were tested only once in a mixed dyad (and could not return to complete a second session).

Overall, 44 dyads were tested: 11 matched pairs of HPs, 10 matched pairs of LPs, and 23 mixed pairs. The order in which dyadic combinations were run across sessions was counterbalanced to distribute the effects of practice.

*Task and procedure* In both sessions, individuals were seated together in a room wearing headphones. They were separated by a partition to prevent visual contact. The task required both participants first to tap along with an isochronous pacing signal (synchronization phase) and then to continue tapping in synchrony with one another after the pacing signal ceased (continuation phase). Each individual tapped on a separate drum pad, which produced percussive feedback sounds that were clearly distinguishable from the other individual's sounds and from the metronome presented during the synchronization phase. After participants had practiced the task, a total of 44 trials were presented across 4 blocks. Participants switched positions (and feedback sounds) between blocks. Trial duration was 40 s, divided into a 20-s synchronization phase followed by a 20-s continuation phase. The dyadic tapping task lasted ca. 45 min.

*Materials and apparatus* Materials and apparatus were identical in both sessions. During the synchronization phase of each trial, a metronome consisting of 40 identical pacing sounds with 500 ms IOIs was presented. Finger tapping performance was registered using two MIDI drum pads (Roland Handsonic HPD-10). The MIDI output of each drum pad was connected to a computer via a MIDI interface. Tap recording and auditory signal presentation were controlled by MaxMSP running under Windows XP Professional. MaxMSP sent MIDI output signals to a digital piano (Yamaha Clavinova CLP 150) that produced different percussion sounds for each drum pad (high or low bongo) and the metronome (claves).

Upon completing the tapping tasks in each session, participants filled out a brief questionnaire addressing their motivation (rated on a 5-point Likert scale) to perform well in the dyadic tapping task. An entire experimental session lasted approximately 1 h.

### *Prior assessment*

Data from two finger tapping tasks run in previous studies were used for the purpose of dyad composition and later analyses.

*Task and procedure* In the first tapping task, the participant was instructed to tap a finger on a drum pad in synchrony with an isochronous pacing signal presented over headphones. After brief practice, the participant completed either 5 or 10 tapping trials with a trial duration of 40 s. In the second task, the participant was instructed to tap a finger in synchrony with a tempo-changing pacing signal. The majority of participants in the current study ($n = 32$) completed a task that was identical to the solo tapping task administered in session C of the current experiment. The remaining participants ($n = 12$) completed a slightly different task with 12 tapping trials and a trial duration of 35–44 s. At the end of the test session, questionnaires addressing musical experience and socio-demographic variables were administered. One questionnaire was designed to measure perspective taking during musical interactions.

*Materials and apparatus* The apparatus in both tasks was identical to the setup used during solo tapping in session C. In the first task, each trial consisted of 40 identical metronome beats (500 ms IOI). The majority of our participants encountered identical materials in the second task as in session C. For the remaining participants, each trial comprised 70–88 identical pacing sounds and contained 9–12 continuous tempo changes spanning a range corresponding to 400–600 ms IOIs. The tempo changes proceeded over 5–11 beats, following sinusoidal or quadratic functions.

## Data analyses

### *Solo tapping*

The degree of synchronization in all solo tapping tasks was measured using linear time series methods. In a preparatory step for linear analyses, pacing sounds and corresponding finger taps were aligned by first assigning each pacing sound to the closest finger tap within a time window of ±200 ms. In a second step, two indicators for individual SMS performance were computed: (1) Mean absolute asynchronies (i.e., the absolute time difference between each finger tap and the corresponding pacing sound) were used as a measure of *individual tapping accuracy*. (2) Variability of asynchronies (i.e., the SDs of signed within-trial asynchronies) was employed as a measure of *individual tapping variability.*

### *Prediction indices*

Based on the aligned solo tapping data, prediction indices were computed for all tasks that measured solo tapping to a tempo-changing pacing signal. Prediction indices were computed based on lag-0 and lag-1 cross-correlations between the ITIs of the participant and the IOIs of the pacing signal (relative to the lag-1 auto-correlation of the sequence; cf. Repp 2002). The ratio of lag-0 over lag-1 CCs reflects the degree that individuals predicted ($\text{ratio} > 1$) versus tracked ($\text{ratio} < 1$) ongoing tempo changes in the pacing sequence. Mean individual prediction indices were computed by averaging individual prediction indices from sessions C and M of the current study.

### *Dyadic tapping*

Conventional linear statistics work well with the small asynchronies that normally arise in simple SMS tasks, like our solo tapping conditions. However, much more variable data can result when two participants are asked to tap in synchrony (without a regular pacing signal), and corresponding finger taps cannot always be easily assigned to one another. Circular statistical methods (e.g., Fisher 1993) obviate this dilemma by mapping all finger taps onto a circular scale, i.e., a unit circle ranging from 0 to 2 $\pi$ in radians (or 0–360 degrees) with the tapping target located at 0 (in radians and degrees). This way, each tap is only interpreted in terms of its angular deviation (or relative phase) from the periodic target, regardless of whether it might have preceded or followed the target.

In the current study, circular analyses were applied to the data measured during the continuation phase of the dyadic tapping task. Our analyses therefore deal with two time series: the finger taps of participant 1 and participant 2. In a preparatory step, these two time series were roughly aligned within a broad window of 1,000 ms. Occasional ITIs larger than 750 ms (and corresponding tap times) were deleted in both time series.[2]

In a second step, the time deviations between the corresponding taps of the two participants were converted into angles in radians.[3] In order to do so, a reference period needed to be defined. In the continuation phase of the current experiment, however, a stable reference frame (e.g., a constant metronome period) was not available. For this reason, tap-to-tap asynchronies were always considered with reference to the current ITI of the tapping partner, i.e., the ITI that just preceded the partner's corresponding tap. The analysis therefore always yields two dyadic measures: one measure for participant 1's performance with respect to participant 2, and vice versa.

In a final step, the radians of all dyadic data points on the circle's circumference were first averaged per trial and then across all trials per dyad. In addition, data from the two participants were averaged to yield an overall measure of joint SMS performance. This common measure is the mean resultant vector of all taps, which is indicative of two aspects of synchronization performance (see Fig. 2).

First, the mean resultant *direction* ($\alpha$) of the vector (i.e., its phase or angular deviation from 0 degrees) informs about the accuracy of SMS performance, analogously to the mean asynchrony in linear statistics. This variable ranges between 0 and 2 $\pi$ in radians, with the corresponding taps of the synchronization partner locked to 0. High SMS accuracy (i.e., low dyadic asynchrony) is reflected in radians close to 0/2 $\pi$.

Second, the mean resultant *length* ($R$) of the vector, which is inversely related to the circular variance ($S$) of the distribution, is informative about the tap-to-tap variability

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[2] This deletion was necessary because ITIs of one participant were used as reference period to estimate the other participant's tapping performance, and vice versa. Each missing tap of one participant results in an artifactually large ITI, which misleadingly suggests that the 'non-missing' tap of the second participant occurred in anti-phase.

[3] Note that signed tap-to-tap asynchronies were used for the calculation of dyadic SMS variability, while dyadic SMS accuracy was based on absolute asynchronies. Absolute values were necessary for the latter, because otherwise vector directions of the two participants cancel each other out when averaged.

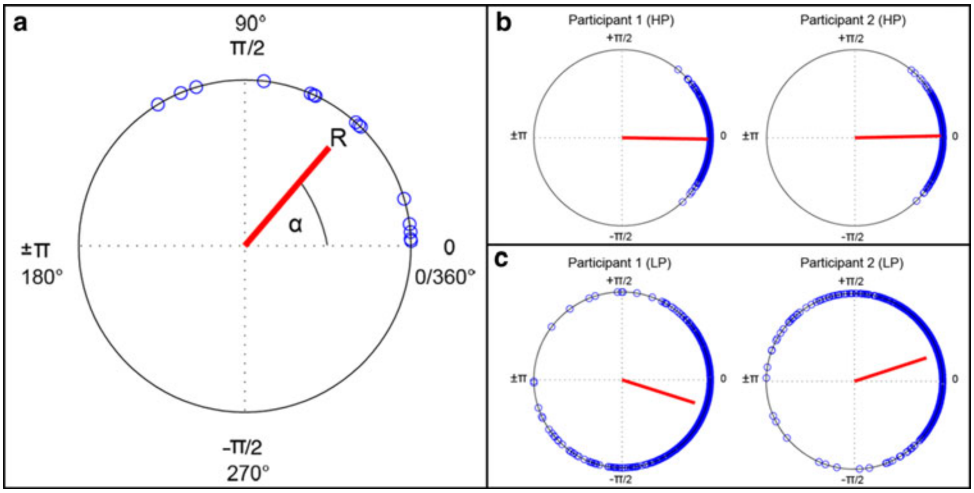

**Fig. 2** Schematic depiction of the synchronization measures and exemplary tapping data. The *left portion* of the figure (**a**) depicts an example data set for one participant from a dyadic tapping trial. The participant's finger taps are shown as data points distributed around a unit circle. Finger taps of the synchronization partner are locked to 0. The *bold line* indicates the direction (α) and length (R) of the mean resultant vector. α increases with increasing time difference between the participants' finger taps. The length of the vector (R) inversely indicates the circular variance (S): the higher R (i.e., the longer the line), the smaller the variability of SMS performance. The *right portion* of the figure shows complete data of dyadic tapping sessions of the most (**b**) and least (**c**) successful pairs. Results are plotted separately for the two pair members (*left* and *right*). Participants in the *upper panel* (**b**; two high-predicting (HP) individuals) synchronized their finger taps with higher accuracy and lower variability than participants in the *lower panel* (**c**; two low-predicting (LP) individuals)

of SMS performance, analogously to the variance of asynchronies in linear statistics. Circular variance ranges between 0 and 1, with lower scores indicating a more unimodal distribution of data points on the circle and thus lower dyadic variability.

Visual inspection of the individual tapping data confirmed unimodal tap distributions, indicating that all participants synchronized their finger taps with a single target (i.e., the taps of their interaction partner). Rayleigh's test for circular uniformity reached significance for all trials of all participants (*ps* $< .05$), speaking for a non-uniform (unimodal) distribution.

To investigate differences in SMS performance between the three dyadic configurations, the two circular measures of dyadic SMS performance were entered into separate (adjusted) univariate analyses of variance (ANOVAs) with dyad type as factor. Because mean vector directions cannot be treated linearly, each dyad's α value was transformed into its linear $x$ and $y$ coordinates (cf. Kirschner and Tomasello 2009). The dyadic $xy$-coordinate, which increases with decreasing tapping accuracy, was used as the dependent variable in an (adjusted) ANOVA. Circular variance, which ranges on a linear scale, was analyzed without further data transformation using a one-way ANOVA. Post hoc statistics were corrected for multiple comparisons and calculated one-tailed to test our specific hypothesis that HP pairs show superior performance compared to LP pairs, with mixed pairs at an intermediate level.

### *Predictor variables for dyadic performance*

Additional analyses were conducted to examine possible predictor variables for dyadic SMS performance and to control for the influence of individual SMS ability on dyadic performance. Three predictor variables for dyadic ability were computed based on (1) individual prediction indices (measured prior to dyadic tapping), (2) individual SMS accuracy scores, and (3) individual SMS variability when synchronizing alone with an isochronous metronome (prior assessment). To yield predictor variables for dyadic SMS performance, values of the two individuals of a pair were summed. This was done separately for each variable, yielding three predictor variables that were entered into correlation analyses and hierarchical regressions to test their role in dyadic SMS performance.

All previously described circular analyses were performed with the CircStat toolbox for MATLAB (Berens 2009). All other analyses were conducted using PASW Statistics 18.0.

## Results

### Stability of individual prediction tendencies

Correlation analyses were conducted to investigate the stability of individual prediction tendencies across time. These tendencies were assessed by solo tapping tasks at three measurement points: in prior assessment (P), and in the congruent (C) and mixed session (M) of the current study.

Regarding sessions P and C, we compare prediction indices that were derived from identical tapping tasks. Prediction indices at session M were assessed by tasks including mathematically different tempo changes. Data comparable between sessions were available for 32 participants from session P, 44 participants from session C, and 40 participants from session M. (Two participants did not return for a second session. Data of one participant from one session were accidentally deleted. Another participant yielded a prediction index more than 2.5 SDs from the sample means.) With respect to the data points available, the average time interval between sessions P and C/M was 8 months (in days: M = 245/241, SD = 130/131). The average time interval between sessions C and M was half a month (in days: M = 17, SD = 25), and session order was counterbalanced.

Scatterplots showing the relationship between prediction indices at different measurement points are displayed in Fig. 3. Strong correlations between individuals' prediction tendencies at different measurement points were revealed, both for indices derived from identical tapping sequences (P&C: $r(30) = .87$, $P < .001$) and for values assessed by sequences including different tempo changes (P&M: $r(28) = .76$, $P < .001$; C&M: $r(38) = .77$, $P < .001$).

Despite these strong correlations, prediction indices changed over time. Statistical tests revealed that prediction indices significantly increased in the group of LPs from prior assessment to later measurement points (P–M: $t(20) = 3.58$, $P = .004$; P–C: $t(20) = 8.07$, $P < .001$; corrected for multiple comparisons), while indices decreased slightly in the group of HPs (P–M: $t(22) = -2.63$, $P = .03$; P–C: $t(18) = -4.05$, $P < .001$). This change could be due to a regression toward the mean, as only participants with relatively extreme prediction tendencies were re-invited for the current experiment.

However, group differences in prediction indices were still evident at later measurement points: The group of LPs still displayed significantly lower prediction indices in session C ($t(42) = 7.43$, $P < .001$) and session M ($t(38) = 4.90$, $P < .001$) compared to the HP group.

## Dyadic synchronization performance

Four pairs had to be excluded from the analyses of dyadic synchronization performance: one LP pair because of missing data (more than 25% of taps were missing in 25% of the trials) and three mixed pairs because their SMS performance yielded values more than 2.5 SDs from the sample means (within and across dyad types). The final sample for analysis therefore consisted of 11 HP pairs, 9 LP pairs, and 20 mixed pairs.

### *Synchronization accuracy*

Figure 4a illustrates the average results for synchronization accuracy for the three dyad types. To investigate differences in dyadic SMS accuracy, mean resultant vector directions were entered into a one-way ANOVA with dyad type as factor. As indicated by a significant Levene's test, the ANOVA's assumption of variance homogeneity of the dependent variable over the three dyad types was not met. Hence, adjusted ANOVA procedures were used that do not assume equality of variance.

A Brown-Forsythe test yielded a significant main effect of dyad type ($F^*(2,30.64) = 5.65$, $P = .008$). Post hoc comparisons (corrected for unequal variances and multiple comparisons; Dunnett's T3) revealed that HP pairs synchronized their taps with higher accuracy (i.e., lower asynchrony) than LP pairs ($P = .003$). The performance of mixed pairs was intermediate and did not differ significantly from LP pairs ($P = .12$) and only marginally from HP pairs ($P = .07$).

Additional analyses were conducted to investigate the explanatory power of individual SMS ability for dyadic SMS accuracy. Individual SMS accuracy was not a good predictor variable for dyadic SMS accuracy ($r(38) = .27$; $P = .09$). However, summed individual prediction indices

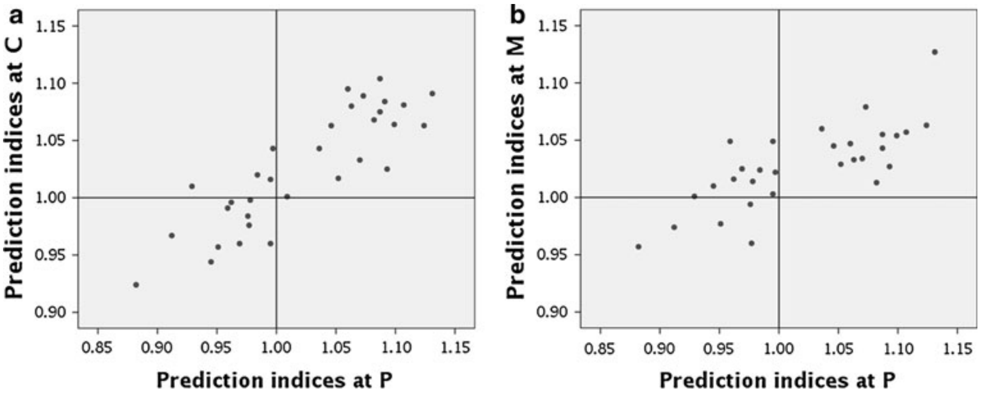

**Fig. 3** Scatterplots of prediction indices measured at prior assessment (P) and in (**a**) the congruent (C) test session and (**b**) the mixed (M) test session

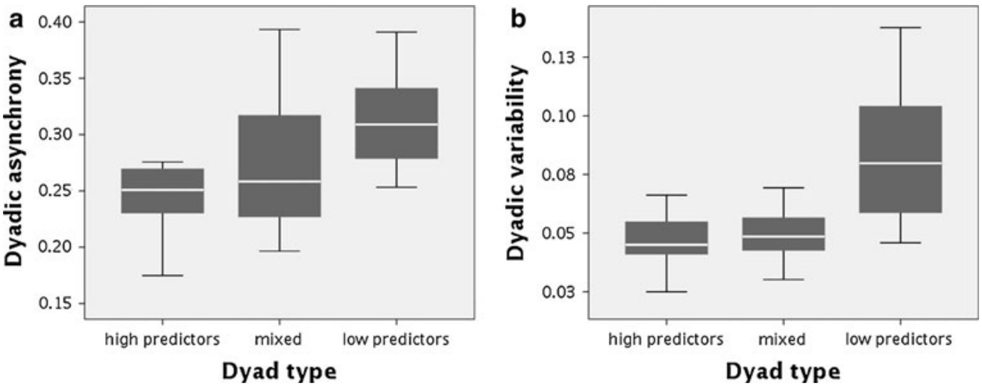

**Fig. 4** Boxplots depicting median (*crossbar*), lower to upper quartile range (*shaded box*), and minimum and maximum values (*whiskers*) for two measures of dyadic synchronization performance separately for the three dyad types. Panel **a** shows dyadic asynchrony, as indexed by vector directions computed by circular statistics. *Lower values* indicate smaller angular deviations from 0 and therefore lower asynchrony, i.e., higher SMS accuracy. Dyads comprising two high-predicting individuals (HP + HP) synchronized their finger taps with higher accuracy (i.e., lower asynchrony) than dyads including two low-predicting individuals (LP + LP). Mixed dyads (HP + LP) were intermediate and only marginally less accurate than HP dyads. Panel **b** depicts dyadic synchronization variability, as indexed by circular variance. HP and mixed dyads synchronized their taps with lower variability than LP dyads

were significantly correlated with dyadic SMS accuracy ($r(38) = -.55$; $P < .001$): Higher summed prediction indices are related to smaller vector angles, reflecting higher dyadic accuracy. When summed prediction indices were entered into hierarchical regression analyses as a predictor variable along with summed SMS accuracy scores, the model's predictions improved significantly ($F_{\text{change}}(1,37) = 13.34$, $P = .001$, $R^2_{\text{change}} = .25$). While summed prediction indices alone explain at least one quarter of the variance in dyadic SMS accuracy ($F(1,38) = 16.13$, $P < .001$, *adjusted* $R^2 = .28$), adding SMS accuracy scores does not significantly improve model predictions ($P = .18$). Together these results indicate that the accuracy of dyadic performance depends more so on the individual prediction tendencies of the co-performers than on individual SMS ability.

### *Synchronization variability*

Figure 4b illustrates the average results for SMS variability for the three dyad types. To investigate differences in tap-to-tap variability in dyadic SMS performance, circular variance scores were entered into a one-way ANOVA with dyad type as factor. The assumption of homogeneity of variances among the three groups was again not met, and adjusted ANOVA procedures were therefore employed.

A Brown-Forsythe test yielded a significant main effect of dyad type ($F^*(2,11.75) = 8.37$, $P = .005$). Post hoc comparisons (Dunnett's T3) revealed that HP and mixed pairs synchronized their taps with less variability than LP pairs ($P = .01$ and $P = .02$). The performance of HP and mixed pairs did not differ significantly ($P = .47$).

As before, correlational and hierarchical regression analyses were conducted to investigate the explanatory power of individual SMS ability for dyadic SMS performance. Dyadic variability was correlated to equal degrees with summed individual SMS variability scores ($r(38) = .57$; $P < .001$) and summed individual prediction indices ($r(38) = -.56$; $P < .001$): Higher summed prediction indices are associated with lower dyadic variance. Hierarchical regression analyses revealed that summed individual SMS variability predicted about one-third of the variance in dyadic SMS variability ($F(1,38) = 18.48$, $P < .001$, *adjusted* $R^2 = .31$). However, when summed prediction indices were added as a second predictor variable, the model's predictions improved significantly ($F_{\text{change}}(1,37) = 8.78$, $P = .005$, $R^2_{\text{change}} = .13$). Hence, individual prediction tendencies explain variance in dyadic SMS performance over and above individual SMS ability.

### *Questionnaire data*

Analyses of questionnaire data indicated that HP and LP participants, considered individually or as the three dyad types, did not differ significantly in their motivation to perform well at the dyadic task (*ps* > .34).

Within the sample of musicians tested ($n = 39$), significant correlations between measures of musical experience and prediction tendencies were observed: Mean individual prediction indices correlated positively with overall musical training (i.e., years of playing/singing summed over all instruments; $r(37) = .62$, $P < .001$), with amount of hours currently practiced per week ($r(37) = .44$, $P < .01$), and with number of instruments played ($r(37) = .44$, $P < .01$). In addition, musicians' prediction indices were significantly positively correlated with the item "To achieve successful ensemble coordination I pay attention to weaker musicians and adapt my playing accordingly” ($r(30) = .41$, $P < .01$) from our musical perspective taking questionnaire.

## Discussion

The aim of the current study was to investigate the role of individual temporal prediction abilities in joint action coordination in a music-related context. Our previous SMS studies revealed individual differences among musicians’ temporal prediction abilities for tempo-changing pacing signals (Pecenka and Keller 2009a, b). The current study adds to these findings by showing that differences in prediction tendencies are stable over time and, moreover, play a role in dyadic synchronization.

Congruent dyads comprising HP individuals with high temporal prediction tendencies synchronized their finger taps with higher accuracy (i.e., lower asynchrony) and less variability than dyads comprising LP individuals with lower temporal prediction tendencies. Dyads composed of individuals with different temporal prediction tendencies (i.e., mixed dyads including HP and LP individuals) showed performance intermediate to the two congruent dyad types. However, mixed dyads’ performances were not clearly influenced by either the HP or the LP individual: With respect to dyadic SMS accuracy, mixed dyads were marginally less accurate than HP dyads and did not differ significantly from LP dyads. In contrast, mixed dyads were significantly less variable in their synchronization performance than LP dyads.

Hierarchical regression analyses revealed that individual temporal prediction tendencies provide a reliable predictor variable for dyadic synchronization performance: The *accuracy* of dyadic SMS performance was significantly better explained by the prediction tendencies of the co-performers than by their individual synchronization accuracy. With respect to dyadic SMS *variability*, performance was equally well predicted by individual prediction tendencies and individual synchronization variability. These differences in the relative explanatory power of prediction tendencies might reflect different sources of inter-individual variance for SMS accuracy and variability. Specifically, individual and dyadic SMS accuracy may both depend to a relatively large degree on temporal predictions mediated by conscious, top-down processes (Repp 2001, 2002). By contrast, SMS variability may vary in large part due to automatic, bottom-up processes, such as rapid adjustments of movement timing related to (phase) error correction and noise in neural timekeeping circuits (Repp 2001, 2005).

We assume that individuals with relatively high prediction tendencies are able to mentally generate precise temporal predictions of upcoming sounds produced by an artificial (computerized) or real co-performer. The precision of these mental predictions, in turn, influences the accuracy with which an individual synchronizes his or her actions with the actual sounds. This assumption is supported by our previous findings from solo tapping studies where individuals with relatively high prediction indices tapped with higher accuracy and lower variability to both tempo-changing and isochronous pacing signals (Pecenka and Keller 2009a, b). Our current study extends this relationship to situations where individuals synchronize their actions with a reactive, human interaction partner.

There is rich empirical evidence suggesting that our own action production system is recruited during the observation of others’ actions (see Rizzolatti and Craighero 2004 for a review). Such a mechanism might not only play a role for action understanding but may also enable us to derive predictions about other people’s action outcomes (see Sebanz and Knoblich 2009 for a review). More precisely, action simulation theories suggest that individuals draw on their own motor system to run internal forward models that simulate the timing of another individual’s actions and thereby predict its future outcome (e.g., Blakemore and Frith 2005; Keller 2008; Knoblich and Jordan 2003; Wilson and Knoblich 2005; Wolpert et al. 2003).

In the domain of musical action coordination, these theories have been supported by the finding that interpersonal action synchronization is more accurate when pianists play the complementary part of a piano duet in time with their own recordings than with other pianists’ recordings (Keller et al. 2007). Studies that investigated action simulation in the domain of sports, where precise timing is also crucial, showed that the accuracy with which individuals predict other people’s action outcomes is influenced by the amount of expertise in that domain (e.g., Jackson et al. 2006; Sebanz and Shiffrar 2009). In line with these findings, positive correlations between the degree of musical training and temporal prediction ability were revealed in our current sample, suggesting that the accuracy with which co-performers’ action outcomes are predicted is fine-tuned over years of musical training. This notion is also consistent with predictive coding models that assume that musical expertise is reflected in more detailed temporal expectancy structures based on the extraction of statistical regularities from the dynamic environment (Vuust et al. 2009).

It should be noted, however, that the anticipation of the future course of others’ actions is presumably just one among many factors contributing to successful interpersonal coordination (Keller 2008; Vesper et al. 2010). As predictions are not necessarily correct, individuals also need to be able to adapt quickly if there is a discrepancy between the predicted and actually perceived actions of others. Recent SMS studies that investigated the underlying mechanisms of interpersonal action coordination have demonstrated that individuals mutually adapt their behavior to one another on a millisecond timescale when tapping in synchrony (Konvalinka et al. 2010) or in alternation with one another (Nowicki 2009). Individual differences in such mutual adaptive timing are likely to play an additional role in determining the quality of interpersonal coordination.

Although the current study did not investigate mutual adaptation between interaction partners on a tap-to-tap basis, results from our questionnaire data point to the importance of interpersonal flexibility for joint action coordination: Individuals with relatively high prediction tendencies (which were associated with successful joint SMS) considered the ability to attend and adapt to others' actions as an important prerequisite for optimal musical ensemble coordination. Nevertheless, it is an open question how and to what degree such beliefs are reflected in actual behavior during joint music making, and, furthermore, whether such domain-specific beliefs also relate to an individual's social abilities outside the musical sphere.

In sum, the results of the current study suggest that individual differences in temporal prediction ability may be an important piece in the puzzle concerning the interaction of cognitive, motor, and social processes that are crucial for interpersonal action coordination in music-related contexts. It remains to be seen whether these findings generalize to other domains of expertise where precise interpersonal action timing is crucial, like sports or dance, or even to everyday joint actions.

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