Mutual Adaptive Timing in Interpersonal Action Coordination

Lena Nowicki and Wolfgang Prinz
Max Planck Institute for Human Cognitive and Brain Sciences,
Leipzig, Germany

Marc Grosjean
Leibniz Research Centre for Working Environment and Human
Factors, Dortmund, Germany

Bruno H. Repp
Haskins Laboratories, New Haven, Connecticut

Peter E. Keller
Max Planck Institute for Human Cognitive and Brain Sciences,
Leipzig, Germany and The MARCS Institute, University of
Western Sydney

Coperformers in musical ensembles continuously adapt the timing of their actions to maintain interpersonal coordination. The current study used a dyadic finger-tapping task to investigate whether such mutual adaptive timing is predominated by assimilation (i.e., copying relative timing, akin to mimicry) or compensation (local error correction). Our task was intended to approximate the demands that arise when coperformers coordinate complementary parts with a rhythm section in an ensemble. In two experiments, paired musicians (the coperformers) were required to tap in alternation, in synchrony with an auditory pacing signal (the rhythm section). Serial dependencies between successive asynchronies produced by alternating individuals' taps relative to the pacing tones revealed greater evidence for temporal assimilation than compensation. By manipulating the availability of visual and auditory feedback across experiments, it was shown that this assimilation was strongest when coactors' taps triggered sounds, while the effects of visual information were negligible. These results suggest that interpersonal temporal assimilation was mediated by perception–action coupling in the auditory modality. Mutual temporal assimilation may facilitate coordination in musical ensembles by automatically increasing stylistic compatibility between coperformers, thereby assisting them to sound cohesive.

Keywords: interpersonal coordination, sensorimotor synchronization, behavioral assimilation

Everyday life typically entails the coordination of one's actions with those of other individuals. Such social interaction frequently requires specific relations in interpersonal movement timing to be produced, as is epitomized in musical ensemble performance (Keller, 2008; Repp, 2006). In ensembles, the actions of multiple individuals must be temporally coordinated in a specific manner in order for the group to produce sounds that give the impression of a coherent musical performance. Thus, each ensemble member temporally tunes his or her actions to those of coperformers. This process relies on sensitivity to deviations from temporal regularity, however subtle, which must be anticipated and reacted to by adjusting the timing of subsequent actions (Keller, 2008; Maduell & Wing, 2007). These adjustments are driven by adaptive timing mechanisms that allow an individual to alter his or her ongoing rhythmic behavior to accommodate the effects of another individual's actions or other external events. The present study used a dyadic finger-tapping task to investigate mutual adaptive timing in interpersonal action coordination.

Our aim was to examine mutual adaptive timing in a tightly controlled experimental setting that nevertheless captures some of the basic demands of temporal coordination between coperformers in musical ensembles. We were specifically interested in demands that arise when coperformers are required to produce complementary actions (i.e., to produce different sounds at different times) in synchrony with a common underlying pulse. This situation is common in modern popular ensemble music (e.g., jazz, rock, and pop), where a "rhythm section" comprising instruments such as the bass guitar and drums provides a basic quasi-periodic pulse relative to which rhythms produced by other instruments are timed. The *basso continuo* (a bass line performed by a keyboard instrument, often supported by another low-pitched instrument) served a similar function in Baroque and other early Western art music (Brendel, 2007). Members of the ensemble must coordinate their

performance with this basic pulse, as well as with each other's sounds, to achieve a well-synchronized holistic musical interplay.

However, synchrony is never (objectively) perfect in human music making owing to perceptual and motor constraints, errors, and uncertainty associated with aesthetically motivated timing deviations that coperformers introduce for expressive purposes (Rasch, 1988). Despite the pervasiveness of asynchronous sounds in ensemble performance, little is known about how the asynchronies produced by one performer affect the timing of actions produced by a coperformer playing a complementary role. The current study therefore sought to elucidate the manner in which paired individuals respond to each other's timing errors produced relative to an externally controlled auditory pacing sequence. It was assumed that the responses that characterize mutual adaptive timing under such circumstances might be subject to the influence of competing processes related to temporal compensation and assimilation.

Temporal compensation entails correcting for errors in movement timing by adjusting the timing of subsequent movements in such a way that the error is reduced. This process has been studied extensively in the context of sensorimotor synchronization paradigms that require an individual to produce simple movements, such as finger taps, in time with isochronous (i.e., evenly timed) or rhythmically varying auditory pacing sequences composed of clicks or tones. Internal timekeepers—that is, interval generators (Wing, 2002) or oscillatory neural processes (Schöner, 2002)—in the individual's central nervous system must be coupled, or entrained, with periodicities marked or implied by the structure of the external pacing signal for sensorimotor synchronization to be successful. In music, multiple internal timekeepers may become coupled with the multiple levels of periodicity in the music's metric structure (Large, 2008; Large & Jones, 1999), giving rise to the experience of hierarchically arranged series of regular internal pulsations (beats) in which every nth pulsation is accented (forming groups, or "bars" of n beats each) (see London, 2004).

Sensorimotor synchronization relies on temporal error-correction processes even when tapping in time with isochronous computer-controlled pacing signals because asynchronies inevitably arise owing to the fact that human movement timing is inherently variable. Without temporal error correction, movement timing variability would accumulate from tap to tap and synchronization would eventually break down (Vorberg & Wing, 1996). Even when synchronization is successfully maintained, finger taps typically precede the onsets of events in the pacing sequence by several tens of milliseconds on the average. The magnitude of this so-called *negative mean asynchrony* has been found to decrease when taps trigger tones that provide auditory feedback (Aschersleben, 2002; Aschersleben & Prinz, 1995). Although musically trained individuals generally exhibit smaller asynchronies than untrained individuals, there are considerable individual differences in the size of the mean asynchrony even among musicians (Aschersleben, 2002; Repp & Penel, 2002).

Temporal error-correction processes keep asynchronies in check by adjusting an individual's timekeeper(s) based on discrepancies between the timing of his or her actions and the pacing sounds (Mates, 1994; Semjen, Schulze, & Vorberg, 2000; Vorberg & Wing, 1996; Vorberg & Schulze, 2002). So long as there are no large-scale tempo changes, this can be achieved automatically via *phase correction*, which involves online adjustments to the way in which the sequence of pulses generated by an internal timekeeper is aligned against the sequence of pacing events (see Repp, 2005). Phase correction is a general process that comes into play in diverse rhythmic behaviors. Research on the dynamics of interpersonal coordination has shown that cyclic movements (e.g., swinging hand-held pendulums, rocking in chairs, and body sway during conversation) become coupled between individuals in the absence of explicit instructions to coordinate, and even when instructed to avoid coordination (e.g., Oullier, de Guzman, Jantzen, Lagarde, & Kelso, 2008; Richardson, Marsh, & Schmidt, 2005; Schmidt & O'Brien, 1997; Shockley, Santana, & Fowler, 2003). Such findings suggest that phase correction is pervasive, automatic, and difficult to suppress.

Theoretical approaches to phase correction—including linear autoregressive models (Mates, 1994; Vorberg & Schulze, 2002) and nonlinear dynamical models (Kelso, Delcolle, & Schöner, 1990; Large, 2000, 2008)—typically assume that the timing of each movement is adjusted so as to compensate for the discrepancy between the timing of the preceding movement and its target pacing event. Under some circumstances, as in the case of occasional timing perturbations, the timing of a pacing event may directly induce a phase-correction response (Repp, 2008, 2011). However, during sensorimotor synchronization with a regular pacing signal or one that is constantly fluctuating in tempo, if a finger tap is much too early relative to a pacing event, then the following tap will be programmed to occur at a relatively late time point. Phase correction thus contributes (negatively) to serial dependencies between successive asynchronies during paced finger tapping (Pressing, 1998). Autocorrelation analyses can be used to quantify the strength of these dependencies and to make inferences about the nature of the adaptive timing mechanisms that underlie them.

Previous work has shown that the lag 1 autocorrelation of asynchronies (i.e., the correlation between the asynchrony series and a copy of itself that has been shifted by one step) is normally positive for tapping with an isochronous metronome (e.g., Repp & Keller, 2008; Semjen et al., 2000; Vorberg & Schulze, 2002; Vorberg & Wing, 1996). This indicates that adjacent taps are generally similar in terms of their timing (earliness or lateness) relative to the pacing signal. This similarity is a consequence of phase drift. Compensatory adjustments associated with typical levels of phase correction are weaker than the tendency to exhibit such phase drift across cycles, which results in positive serial dependencies over both short and long timescales (cf. Torre & Delignières, 2008). However, research using computer simulations and experiments that involve tapping with adaptive pacing signals (which have been endowed with phase-correction capabilities) have demonstrated that the lag 1 autocorrelation approaches zero as the gain of phase correction is increased (i.e., the proportion of each asynchrony that is corrected becomes larger) (Repp & Keller, 2008; Schulze & Vorberg, 2002; Semjen et al., 2000; Vorberg & Schulze, 2002). That amount of gain is considered optimal because it minimizes the variance of the asynchronies (Schulze & Vorberg, 2002). The lag 1 autocorrelation of asynchronies is negative—indicating a zig–zagged pattern of fluctuations in the asynchrony series—when the optimal gain of phase correction is exceeded. This effect is elicited in sensorimotor synchronization tasks using adaptive pacing signals with high phase correction settings and at slow tempi (Repp, Keller, & Jacoby, 2012).

Although temporal compensation may be necessary for an individual to maintain synchrony with sounds produced by a metronome or an ensemble coperformer, it is not known whether compensatory mechanisms in one individual also operate in response to asynchronies produced by another individual when these individuals produce complementary actions in time with an external pacing signal (e.g., a metronome or rhythm section). Such mutual temporal compensation may occur to the extent that phase error correction operates analogously to "contrast effects" found in studies investigating links between perception and action (see Zwickel & Prinz, 2012). Contrast effects are manifest as involuntary compensatory movements that occur when observing an action that deviates from an intended target, as when spectators lean to the left when a football goal kick veers too far to the right (De Maeght & Prinz, 2004).

Temporal compensation is not, however, the only type of response that may characterize mutual temporal adaptation in musical contexts. Research in a number of fields that are relevant to interpersonal coordination has revealed that individuals tend to assimilate their behavior in a variety of circumstances. Behavioral assimilation is seen in displays of nonconscious mimicry where people adopt the facial expressions, speech patterns, mannerisms, and postures of interaction partners (Chartrand & Bargh, 1999). Such effects are suggestive of close links between perception and action (Gallese, Keysers, & Rizzolatti, 2004; Knoblich & Sebanz, 2008; Prinz, Aschersleben, & Koch, 2009; Rizzolatti & Sinigaglia, 2010; Sebanz, Koblich, & Prinz, 2005).

Findings from studies of perception–action links suggest that action observation automatically triggers a process of covert action simulation in the observer's brain (Jeannerod, 2006; Wilson & Knoblich, 2005). In musical ensembles, performers may use online simulation to generate predictions about the timing of events in the ongoing productions of their coperformers (Keller & Appel, 2010; Keller, Knoblich, & Repp, 2007). Such prediction enables the use of anticipatory control strategies that are based on the integrated effects of one's own and others' action timing (Keller, 2008; Knoblich & Jordan, 2003), thereby allowing interpersonal behavior to be coordinated smoothly within the real-time constraints of performance.

Covert simulation can lead to overt mimicry unless the observer is otherwise occupied or intentionally inhibits an overt response (Chartrand, Maddux, & Lakin, 2005). Even when full-blown mimicry is checked, however, the simulation process triggered by perceiving (or imagining) an action can activate a corresponding representation in the performer's motor system (cf. Sebanz, Bekkering, & Knoblich, 2006; Vlainic, Liepelt, Colzato, Prinz, & Hommel, 2010), leading to behavioral assimilation during ongoing action execution (see Jung, Hollaender, Mueller, & Prinz, 2011). In this sense, an individual's style of action execution may be mimicked (e.g., in terms of its general kinematic properties) even when the specific action that they perform is not (Keller et al., 2007). Action simulation may lead to this form of behavioral mimicry in musical contexts (cf. Overy & Molnar-Szakacs, 2009), and such mimicry may facilitate the communicative interplay of musicians in ensembles (Schögler, 1999–2000). Behavioral assimilation may thus assist coperformers in achieving a cohesive ensemble sound. This raises the possibility that an individual's responses to another's timing errors during paced sensorimotor

synchronization may be characterized by temporal assimilation in addition to, or instead of, temporal compensation.

The current study used a dyadic sensorimotor synchronization paradigm to investigate mutual adaptive timing. The task required the two members of a coacting dyad to tap in alternation, in synchrony with an isochronous auditory metronome, with or without auditory and visual feedback. Note that this "paced dyadic alternation" task does not require participants to tap in synchrony with one another, but rather to take turns at producing taps in synchrony with the sounds of an external pacing signal. This task was intended to approximate the basic demands of coordinating different musical parts in an ensemble with a rhythm section.

Although several recent studies have focused on dyadic synchronization between individuals tapping in an in-phase relationship to one another without an external pacing signal (e.g., Konvalinka, Vuust, Roepstorff, & Frith, 2010; Maduell & Wing, 2007; Merker, Madison, & Eckerdal, 2009; Pecenka & Keller, 2011), we used a task characterized by antiphase interpersonal coordination in synchrony with an external signal to assess serial dependencies between successive asynchronies produced by either one actor or both coactors. This allowed us to interrogate the adaptive timing mechanisms that enable interpersonal temporal coordination using lagged autocorrelation analyses similar to those used in studies of temporal error correction.

Our research question was whether mutual adaptive timing occurs during paced dyadic alternation, and, if so, the form that it takes. One possible outcome is that interpersonal tap timing could exhibit no systematic serial dependencies (reflected in zero lag l autocorrelation), if, for example, coactors ignore each other's performance or achieve optimal phase correction (see Schulze & Vorberg, 2002). Another possibility is that interpersonal tap timing is characterized by extreme compensation (i.e., negative lag 1 autocorrelation) owing to increases in the gain of phase correction in response to challenges raised by the task (cf. Repp & Keller, 2008). Finally, mutual adaptation during paced dyadic alteration may take the form of temporal assimilation (i.e., each coactor mimicking the other's tap timing). Such assimilation would be indicated by the lag 1 autocorrelation of asynchronies generated by the taps of two alternating individuals being greater than zero (as in phase drift), and, importantly, the degree of autocorrelation increasing with increasing availability of feedback about the other's action timing. Although research that is relevant to interpersonal coordination has yielded evidence for behavioral assimilation in diverse contexts, it was not known whether temporal assimilation would be observed for interpersonal serial dependencies in asynchronies at the millisecond timescale investigated here.

We report two experiments that addressed the above issues. The first experiment did so by varying the task (paced dyadic alternation vs. solo tapping) and the type of information that each individual had access to about their coactor's tap timing (auditory and visual vs. visual feedback only). The second experiment further investigated the roles of auditory and visual feedback in mutual adaptive timing. Figure 1 illustrates the experimental tasks and conditions.

Experiment 1

The main aim of Experiment 1 was to test for evidence of mutual adaptive timing in paced dyadic alternation. To this end,

A Tapping Task

Joint   Solo

Pacing signal | | | | | |... | | | | | |...
Finger taps   ● ○ ● ○ ● ○

● Participant 1 | | | | | |...
○ Participant 2   ○   ○   ○

B Auditory Feedback

Visual Feedback

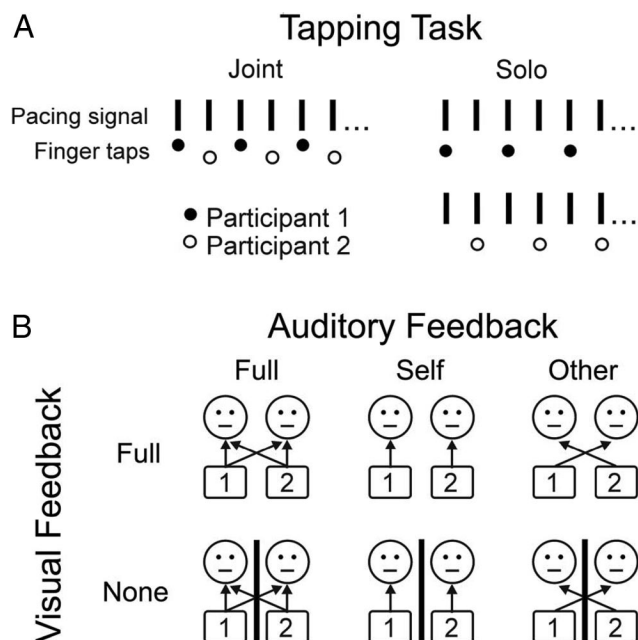Full   Self   Other

Full

None

Figure 1. Panel (A) provides schematic representations of the tapping tasks used in Experiment 1 (joint and solo tapping) and Experiment 2 (joint tapping only). Vertical lines indicate pacing signal events (percussion sounds), and filled and unfilled circles represent target times for finger taps produced by the two participants in a dyad. Panel (B) illustrates the visual feedback and auditory feedback conditions used in Experiment 2. Rectangles labeled "1" and "2" represent percussion pads tapped on by the two participants, and arrows indicate the flow of auditory feedback (percussion sounds triggered by taps) to both participants (Full) or to just a single participant (Self and Other). The top row of diagrams in panel B depicts conditions in which participants received visual feedback (Full); the bottom row uses a vertical line between participants to indicate the absence of visual feedback (None).

pairs of musically trained participants tapped in alternation in synchrony with an isochronous auditory pacing signal under two conditions. In one group of participants, the taps of both individuals within a dyad triggered distinctive sounds, whereas in another group, taps did not trigger sounds. Participants in both groups were seated beside one another and could see one another clearly. The experimental conditions will henceforth be referred to as "A_{full}" (indicating the presence of auditory feedback) and "A_{none}" (indicating the absence of auditory feedback). To assist coactors in turn-taking, they were instructed to imagine that the pacing signal was structured according to a duple meter consisting of alternating strong and weak beats, with one person tapping on strong beats and the other on weak beats.

It was expected that mutual adaptive timing based on coupling in the auditory modality would occur when coacting individuals have access to auditory cues about the timing of each others' taps relative to the pacing signal. We assumed that such mutual adaptive timing would be reflected in serial dependencies between successive asynchronies generated by the two individuals. On the other hand, when coacting individuals cannot hear each others' asynchronies (with the pacing signal), there should be little evidence for serial dependencies related to mutual adaptive timing.

Any apparent serial dependencies in this condition would be attributable to visual feedback and/or incidentally similar types of serial correlations in each individual's tap time series (e.g., owing to common patterns of phase drift). Mutual adaptive timing was assessed by computing the *joint lag 1 autocorrelation*, which is the lag 1 autocorrelation for the series of asynchronies associated with the alternating taps of the two participants in each dyad. Positive values of the joint lag 1 autocorrelation coefficient suggest a greater tendency for temporal assimilation than compensation in mutual adaptive timing, whereas negative values indicate the opposite.

A secondary aim of Experiment 1 was to investigate effects of mutual adaptive timing on each individual's own actions during paced dyadic alternation. Specifically, we were interested in whether the process of adapting one's action timing to that of another individual (e.g., via assimilation and/or compensation) affects the temporal error-correction mechanisms that keep one's own actions synchronized with the pacing signal. This may occur, for instance, if mutual adaptation disrupts the operation of phase correction related to one's own taps. To test this possibility, we compared serial dependencies between successive asynchronies generated by each participant when tapping with a coactor in alternation (T_{joint} task) and when tapping alone on every other event of the pacing signal (T_{solo} task). If mutual adaptive timing interacts with the process of correcting one's own timing errors, then these *individual lag 1 autocorrelations* should differ when tapping in alternation with another and when tapping alone.

Method

Participants. Sixty individuals recruited from the database of the Max Planck Institute for Human Cognitive and Brain Sciences participated in the experiment. All were right-handed, aged between 18 and 30 years, and had played at least one musical instrument regularly for >2 years. The participants were quasi-randomly paired to form approximately equal numbers of female dyads, male dyads, and mixed sex dyads (although type of pairing was not expected to affect performance). Participants within a dyad did not know each other before coming to the lab. Fifteen dyads were allocated to the A_{full} condition (in which taps triggered sounds), and 15 dyads were allocated to the A_{none} condition (in which taps did not trigger sounds).

For A_{full} dyads, mean age was 23.17 years with a standard deviation of 2.72 years. Participants in this group played, on average, 1.77 (*SD* = 0.80) instruments for 11.80 years (*SD* = 3.22; range: 7–20 years). Eleven out of the 30 individuals had no ensemble experience, whereas the others had played in an ensemble for, on average, 7.13 years (*SD* = 3.17; range: 2–14 years). Data from two dyads from this group were excluded from the final analyses because of a large number of missing taps. The remaining 13 dyads comprised three female, five male, and five mixed sex pairs.

For A_{none} dyads, mean age was 24.14 years with a standard deviation of 3.24 years. Individuals in this group played, on average, 1.96 (*SD* = 0.95) instruments for 12.09 years (*SD* = 5.05; range: 4–24 years). Eleven out of the 30 participants had no ensemble experience, and the others had played in an ensemble for 6.79 years, on average (*SD* = 3.30; range: 2–14 years). Again, data from two dyads were excluded from analyses owing to missing taps. The remaining 13 dyads included four female, five male, and four mixed sex pairs.

Design. A $2 \times (2)$ mixed design was used, with Auditory Feedback (A_{full} vs. A_{none}) manipulated as a between-participants independent variable and Tapping Task (T_{joint} vs. T_{solo}) as a within-participants variable. The chief dependent variables were the joint lag 1 autocorrelation of asynchronies (for the T_{joint} task) and the individual lag 1 autocorrelation of asynchronies (for the T_{joint} and T_{solo} tasks). Mean asynchronies and the variance of asynchronies were also examined to provide objective evidence concerning the degree to which participants successfully performed the instructed task of synchronizing with the pacing signal across the different tasks and feedback conditions.

Materials and apparatus. The same isochronous pacing signal was used in all conditions. It consisted of a metronomic sequence of 41 piano tones with an interonset interval of 428.57 ms (i.e., 140 beats per minute). This sequence length was chosen to match the length of a rhythmical pacing sequence based on a musical piece (Badinerie from Suite No. 2 in B minor by Johann Sebastian Bach) that was also included in the current study. However, we will not report the results for this musical piece, as it was included for reasons that extend beyond the scope of the present article.

Events in the metronomic pacing sequence were specified in a preprogrammed Musical Instrument Digital Interface (MIDI) file created with Finale, 2000 software. The initial six tones of the sequence had pitch D5, a nominal duration of a quarter note each (as specified in Finale notation), and intensity accents that marked a duple metric pattern consisting of alternating strong and weak beats (MIDI velocity 88 and 49, respectively). Each of the 35 tones that followed had pitch D3, a nominal duration of a quarter note, and constant intensity (MIDI velocity 75).

Presentation of the MIDI pacing sequence was controlled by a program written in MAX/MSP 4.5.7 software running on a Macintosh G5 computer. Piano tones were generated by the built-in QuickTime Music Synthesizer.

Two identical MIDI percussion pads (Roland SPD-6) were used to register finger taps. The percussion pads, which were set to "manual" (as opposed to "drumstick") mode, were connected to the G5 computer via a MIDI interface (M-Audio MIDISPORT 4 $\times$ 4). The surface of each percussion pad is divided into two rows of three segments. In the A_{full} condition, taps on the top left segment and top right segment triggered different percussion sounds generated by the synthesizer on the G5 computer: "claves" for the left segment and "low bongo" for the right segment. Tap onset times were recorded by the same MAX/MSP program that controlled the presentation of the pacing sequence.

The audio output of the computer was routed to two sets of Sennheiser HD 270 headphones.

Procedure. Participants were invited to the laboratory in pairs. The two individuals were seated on chairs next to one another, facing an experimenter who sat at the opposite side of a table. After the T_{joint} and T_{solo} tasks were explained to the participants in detail, they were asked to read and sign a consent form if they still wished to take part in the experiment (which all of them did). During the experiment, each participant wore headphones and held a percussion pad on his or her lap. Participants also wore disposable foam earplugs, which blocked the sounds of their fingers impacting on the surface of the percussion pads. The tones of the pacing sequence and the percussion sounds triggered by taps (in the A_{full} condition) were presented over the headphones at a comfortable intensity level.

Participants in the A_{full} group and the A_{none} group performed both the T_{joint} and the T_{solo} task. They were given ample opportunity to practice each task before data collection commenced. Each trial of the tasks consisted of a single presentation of the pacing sequence. Trials were initiated by the experimenter pressing the spacebar of the computer keyboard when the participant(s) indicated readiness.

In T_{joint} trials, the two participants from a dyad were instructed to tap in alternation, with one individual tapping on strong beats, and the other on weak beats, of the duple meter established by the first six tones of the pacing sequence. Participants were asked to imagine that this pattern of accentuation continued throughout the remainder of the sequence (i.e., even when the tones had equal intensity). The participant assigned to strong beats was asked to commence tapping with the third tone, and the other participant with the fourth tone, of the pacing sequence, and to continue tapping until the sequence ended. One individual from the dyad tapped with the index finger of the right hand on the top left segment of their percussion pad and the other individual tapped with the right index finger on the top right segment of their pad (this was counterbalanced across blocks; see below). Each individual could clearly see the other's tapping finger, although they were not explicitly instructed to watch each other. Task instructions specified that participants should tap together, as a pair, in alternation in synchrony with the pacing signal.

In T_{solo} trials, one member from the dyad tapped, whereas the other remained still. The active participant was instructed to tap with every other tone of the pacing sequence, starting with the third tone. Participants thus tapped alone on metrically strong beats only (because it was assumed that this was easier than tapping on weak beats). They tapped with the right index finger on the same segment of the percussion pad as in the joint condition.

Members of A_{full} dyads, who could both hear and see each other tapping, completed four blocks of six T_{joint} trials and four blocks (two per participant) of six T_{solo} trials with the isochronous pacing sequence.[1] Members of A_{none} dyads, who could see but not hear each other, completed four blocks of five T_{joint} trials and four blocks of five T_{solo} trials.[2]

For both groups of participants, T_{joint} and T_{solo} blocks were presented in counterbalanced alternating orders. One-half of the dyads in each group started with a T_{joint} block and the remaining dyads started with a T_{solo} block. The individual who tapped alone during a given T_{solo} block tapped on the metrically strong beats in the subsequent T_{joint} block (and had tapped on the weak beats in the previous T_{joint} block). Thus, each participant encountered the T_{solo} condition in two

---

[1] An additional six T_{joint} trials and six T_{solo} trials were included in each of these blocks. These additional trials used the Badinerie from Suite No. 2 in B minor by Johann Sebastian Bach as a musical pacing sequence. Trials featuring the musical and metronomic pacing signals were intermixed randomly within blocks. The results obtained with the musical piece (which were similar to those for the metronome, except that the variability of asynchronies was relatively high) will not be reported here. It suffices to note that the musical piece served to reinforce the duple meter that participants were instructed to imagine when tapping with the metronomic signal.

[2] In each block, participants in the A_{none} group encountered an equal number of trials paced by the same musical piece as was used with the A_{full} group (see Footnote 1). The difference in the number of trials encountered by participants in the A_{full} and A_{none} groups is related to the fact that these conditions were originally conceived as separate experiments. We have no reason to believe that the results and conclusions of this study were compromised by this difference.

blocks, and tapped on the metrically strong beat in two blocks and on the metrically weak beat in two other blocks of the T_{joint} condition.

Data analysis. Data analysis proceeded in two steps. First, raw asynchronies for each trial were computed by subtracting the onset time of each event in the pacing sequence from the nearest registered tap time. A constant of 28 ms was subtracted from each asynchrony to account for an empirically verified processing delay in the MIDI setup. Trials with missing taps (owing to insufficient tapping force or asynchronies outside a $\pm$ 200 ms range) were excluded from the final analyses. Raw asynchronies from remaining trials were averaged to give a measure of mean asynchrony, and their variance was calculated to yield an inverse measure of performance stability, for each participant in each trial. This averaging was done separately for each participant in trials from the T_{joint} condition. Mean asynchrony and variance measures were then averaged across trials within each condition for each participant.

The time intervals between each individual's taps in T_{joint} and T_{solo} trials, and between the taps of coacting individuals in T_{joint} trials, were also analyzed to assess the stability of tapping tempo. We will not report results for this measure in the current article, though it can be mentioned that tapping tempo was stable across conditions owing to the presence of the isochronous pacing sequence.

The second step in data analysis addressed serial dependencies in tap timing by examining the lag 1 autocorrelation of asynchronies generated by coacting members of a dyad and by each individual alone.

Joint lag 1 autocorrelation coefficients were computed for series of asynchronies produced by the alternating taps of the two individuals in T_{joint} trials. These analyses were conducted on 'relative,' rather than raw asynchronies. Relative asynchronies were calculated separately for each individual's tap series from each T_{joint} trial by subtracting the individual's mean asynchrony for the given trial from each of the asynchronies that he or she produced in the trial. The effects of individual differences in mean asynchrony (which introduced a strong, but artifactual, negative lag 1 autocorrelation) were thus partialed out of the T_{joint} lag 1 autocorrelation estimates.

Individual lag 1 autocorrelation coefficients were computed for asynchronies produced by each individual participant when tapping with his or her partner in T_{joint} trials and when tapping alone in T_{solo} trials. The analysis of individual lag 1 autocorrelations was restricted to asynchronies produced when tapping with metrically strong beats in T_{joint} trials, as participants tapped only on strong beats in T_{solo} trials.

Results and Discussion

A total of 30 out of the 936 trials completed by participants in the A_{full} Auditory Feedback group (3.21%) and 37 out of 780 trials in the A_{none} group (4.74%) contained missing taps and were excluded from the analyses reported below.

Mean asynchronies and mean within-trial variance of asynchronies for the two tasks—averaged across participants in each of the two Auditory Feedback groups—are displayed in Figure 2. In Figure 2A, it can be seen that mean asynchronies were generally negative and fairly constant across the T_{joint} and T_{solo} tapping tasks. However, mean asynchronies were clearly smaller (less
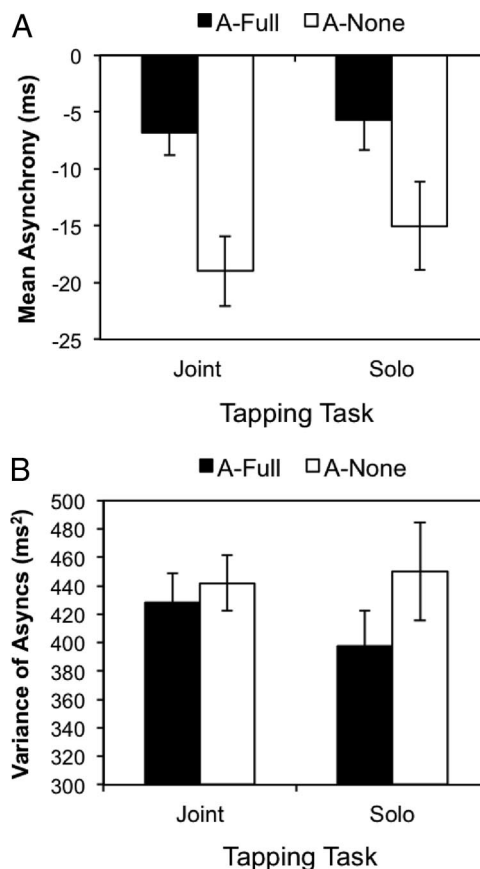

Figure 2. Mean asynchronies (panel A, in ms) and within-trial variance of asynchronies (panel B, in ms^2) averaged across participants for each task (joint, solo) and feedback condition (A_{full}, A_{none}) in Experiment 1. Error bars represent the standard error of the mean.

negative) in the A_{full} than the A_{none} group. An Analysis of Variance (ANOVA) conducted on these data revealed a statistically significant main effect of Auditory Feedback (A_{full} vs. A_{none}), $F(1, 50) = 8.01$, $p = .007$, whereas the Tapping Task main effect (T_{joint} vs. T_{solo}) and the Auditory Feedback $\times$ Tapping Task interaction were not significant, $F(1, 50) = 1.97$, $p = .167$ and $F(1, 50) = 0.62$, $p = .435$, respectively. These results indicate that the size of the negative mean asynchrony was not affected by whether an individual tapped alone or in alternation with another individual, but it was modulated by the presence of auditory feedback. Specifically, as has been observed in previous studies (see Aschersleben, 2002), asynchronies were less negative—thus synchronization was more accurate—when taps triggered sounds than when they did not.

The variance of asynchronies, which can be seen in Figure 2B, was constant across groups and tasks. An ANOVA on these data did not yield statistically significant effects of Auditory Feedback, $F(1, 50) = 1.23$, $p = .273$, Tapping Task, $F(1, 50) = 0.29$, $p = .591$, or their interaction, $F(1, 50) = 0.89$, $p = .350$. This suggests that the stability of synchronization was commensurate under conditions where taps did or did not trigger sounds when an individual acted alone or in alternation with a coactor.

We turn now to the results of the main analyses, which addressed mutual adaptive timing by measuring serial dependencies

between asynchronies generated by two individuals (in T_{joint} trials) and by single individuals (in T_{joint} and T_{solo} trials). Evidence for mutual adaptive timing during T_{joint} trials was assessed by examining the effects of Auditory Feedback—that is, whether or not coacting individuals could hear (in addition to see) one another—on the joint lag 1 autocorrelation of asynchronies. Average joint lag 1 auto-correlation coefficients for the A_{full} and the A_{none} group are displayed in Figure 3A (all correlation coefficients were subject to Fisher's z transformation prior to analysis). The first thing that can be noted is that coefficients in both conditions are positive and significantly greater than zero, $t(12) = 8.78, p = .000$ for A_{full} and $t(12) = 2.89, p = .013$ for A_{none}. This implies a stronger tendency for temporal assimilation than compensation in mutual adaptive timing. Moreover, joint lag 1 autocorrelation coefficients are much higher for dyads in the A_{full} group than in the A_{none} group, $t(24) = 4.36, p = .000$. These results suggest that mutual adaptive timing during paced dyadic alternation is characterized by a general tendency for temporal assimilation (but see below for a caveat), and that this assimilation is stronger when coacting individuals can both see and hear one another than when they can only see one another.

To investigate the effects of mutual adaptive timing on each individual's own actions, we compared individual lag 1 autocor-

A

B

Figure 3. Average joint lag 1 autocorrelation (AC1) of asynchronies for the A_{full} and A_{none} auditory feedback conditions in the joint task (panel A) and average individual lag 1 autocorrelation of asynchronies for the two feedback conditions in the joint and the solo task (panel B) in Experiment 1. Error bars represent the standard error of the mean.

relations of asynchronies in the T_{joint} task with those in the T_{solo} task (wherein each individual tapped alone on strong beats of the pacing signal). Averaged individual lag 1 autocorrelation coefficients are shown in Figure 3B. All coefficients are positive, significantly greater than zero ($ps < .001$), and very similar in magnitude. An ANOVA on these data indicated that there were no significant effects of Auditory Feedback, $F(1, 50) = 0.28, p = .598$, Tapping Task, $F(1, 50) = 0.18, p = .676$, or their interaction, $F(1, 50) = 0.94, p = .337$. The lack of a significant effect of Tapping Task is noteworthy insofar as it indicates that serial dependencies between one's own taps were not affected by the intervening taps produced by one's partner. The absence of significant effects of Auditory Feedback indicates that this was the case regardless of whether or not coacting individuals received auditory information about the timing of each other's taps. These findings suggest that mutual adaptive timing does not influence the process of correcting one's own timing errors. This conclusion is moderated, however, by the fact that the correlation between (z-transformed) individual lag 1 autocorrelation coefficients in the T_{joint} and T_{solo} conditions was only moderate, though significant, for participants in the A_{full} group ($r(24) = .49, p = .01$) and weak for participants in the A_{none} group ($r(24) = .30, p = .14$). This raises the possibility that mutual adaptive timing may affect one's own error-correction processes, but in different ways for different individuals.

In sum, the results of Experiment 1 provide evidence that mutual adaptive timing during paced dyadic alternation is characterized by temporal assimilation; for example, if a tap produced by one individual is very early relative to the pacing signal, then the next tap produced by the other individual will also tend to be correspondingly early. However, the process of adapting one's action timing to that of another individual via assimilation does not consistently disrupt the temporal error-correction mechanisms that keep one's own actions synchronized with the pacing signal. This may be the case because coupling between each individual and the pacing signal is stronger than coupling between the two coacting individuals (assuming that such coupling is present). Indeed, work taking a dynamical systems approach to movement coordination has shown that in-phase coupling (tapping in synchrony with the pacing signal in our task) is stronger than antiphase coupling (tapping in alternation with another individual) for range timing tasks (see Schmidt & Richardson, 2008).

The interpersonal temporal assimilation that we observed was most pronounced when coacting individuals could hear, as well as see, the effects of each others' actions. Synchronization was also most accurate (i.e., asynchronies were closest to zero) under such conditions. These findings suggest that coupling between each individual and the pacing signal, and coupling between the two coacting individuals, are both strongest when mediated by the auditory modality. Mutual temporal assimilation may therefore be based upon information about the relationship between the timing of sounds triggered by one's own and the other's actions. The relative influence of auditory and visual information on mutual adaptive timing was explored further in a second experiment.

Experiment 2

Experiment 2 had two main aims. The first was to investigate the nature of the contribution of auditory feedback to mutual
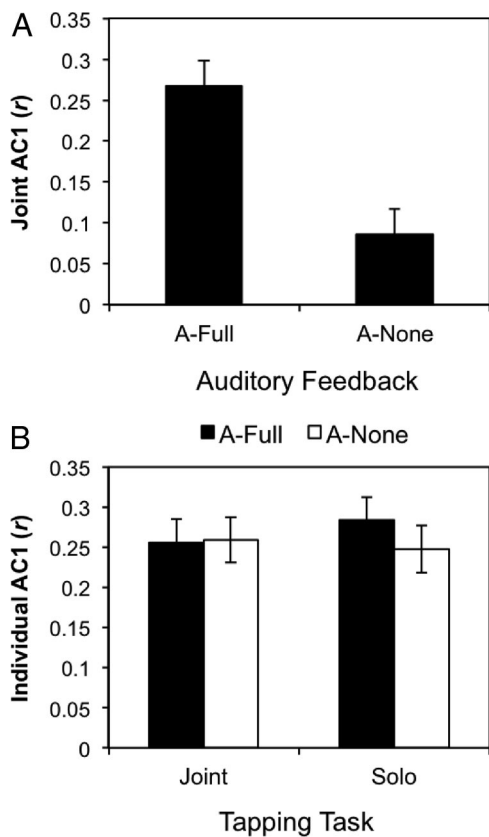
adaptive timing. We were specifically interested in the degree to which temporal assimilation during paced dyadic alternation is driven by interpersonal coupling in the auditory modality. To investigate this issue, we varied the source of auditory information that was available to coacting individuals in such a way that each individual could hear sounds triggered by (i) their own taps and their partner's taps, (ii) only their partner's taps, or (iii) only their own taps (cf. Mates, Radil, & Pöppel, 1992). If temporal assimilation relies on feedback about the relationship between the timing of sounds triggered by one's own and the other's actions, then restricted access to such feedback should *lessen* serial dependencies between coactors' taps. Thus, joint lag 1 autocorrelation coefficients should be lower when participants only hear sounds produced by their own or their partner's taps relative to when they hear sounds produced by both individuals' taps. However, if auditory feedback about a partner's tap timing is sufficient for temporal assimilation, then joint lag 1 autocorrelation coefficients should remain high even when participants only hear sounds triggered by their partner's taps but not their own taps. This may be the case if auditory perception of the partner's phase errors directly affects one's own motor timing analogously to the well documented effects of timing perturbations in a metronome (see Repp, 2005) and the "attractor" effects that arise when out-of-phase "distracter" sequences are interleaved with a "target" pacing signal (Repp, 2004).

The second aim of the current experiment was to ascertain whether the apparent evidence for temporal assimilation found when coacting individuals could see but not hear one another in the A_{none} condition of Experiment 1 is attributable to mutual adaptive timing mediated by visual feedback. It may be the case that latent similarities between serial correlations in each individual's tap time series (e.g., drift owing to common processes such as $1/f$ noise; see Torres & Delignières, 2008) provide a partial or full explanation of the positive joint lag 1 autocorrelation coefficients that we observed in the A_{none} condition. This issue was addressed in the current experiment by including a condition in which members of a dyad could neither hear nor see each other. Joint lag 1 autocorrelation coefficients should remain higher when visual feedback is present than when it is absent if visual information about a coactor's tap timing contributes to temporal assimilation during paced dyadic alternation.

In addition to the above aims, we reexamined the issue of whether mutual adaptive timing affects the process of correcting one's own timing errors. This was done by analyzing the effects of visual and auditory feedback on individual lag 1 autocorrelations of asynchronies generated during paced dyadic alternation. In contrast to Experiment 1, auditory feedback was varied as a within-participants factor in Experiment 2.

Method

Participants. Twenty-six individuals participated in Experiment 2. All were musically trained and none had participated in Experiment 1. Mean age was 23.69 years with a standard deviation of 3.22 years. Participants played, on average, 1.46 ($SD = 0.75$) instruments for 12.73 years ($SD = 5.10$; range: 5–25 years). Six out of the 26 participants had no ensemble experience, whereas the others had played in an ensemble for, on average, 6.33 years ($SD = 3.22$; range: 1–12 years). Participants were quasi-randomly paired to form 13 dyads. Data from one dyad could not be analyzed owing to a large number of missing taps. The remaining 12 dyads comprised two female, one male, and nine mixed sex pairs.

Design. Visual Feedback (V_{full} = present; V_{none} = absent) and the source of Auditory feedback that was available to coacting individuals (A_{full} = sounds triggered by both individuals' taps; A_{other} = sounds triggered only by the other's taps; A_{self} = sounds triggered only by one's own taps) were manipulated in a 2×3 repeated measures design.

Procedure, materials, apparatus, and data analysis. Participants were invited to the laboratory in pairs to perform the paced dyadic alternation task, as in Experiment 1 (solo tapping was not required in Experiment 2). The pacing signal was the same isochronous sequence of piano tones as used in Experiment 1. The apparatus used to present the pacing signal and to record participants' taps was also the same, apart from the fact that the audio output of the computer and the percussion pads was routed to the two sets of headphones via two separate stereo amplifier systems (Dynavox conditional stimulus [CS]-PA1). This setup allowed the auditory feedback available to the two individuals within a dyad to be controlled independently.

Participants completed 12 blocks of eight paced dyadic alternation trials. Members of a dyad could see one another in six blocks of trials (V_{full}) and could not see one another in the other six blocks (V_{none}). An opaque screen (150 cm high $\times$ 122 cm wide) was placed between the members of a dyad to eliminate visual feedback in the V_{none} condition. The order in which the two Visual Feedback conditions were encountered was counterbalanced across dyads.

In each Visual Feedback condition, participants could hear sounds triggered by each others' taps in two blocks of trials (A_{full}), they heard only sounds triggered by their partner's taps in two blocks (A_{other}), and they only heard sounds triggered by their own taps in two blocks (A_{self}). The order in which these three Auditory Feedback conditions were run was counterbalanced across dyads. As in Experiment 1, auditory feedback consisted of clave sounds triggered by taps on one percussion pad and bongo sounds triggered by taps on the other percussion pad.

Data were analyzed in similar fashion to those from Experiment 1.

Results and Discussion

Fifty-four out of the 1,152 trials (4.69%) from the experiment contained missing taps and were excluded from the analyses reported below.

Average values for mean asynchrony and the variance of asynchronies in the different Visual Feedback and Auditory Feedback conditions are displayed in Figure 4. It can be seen in Figure 4A that mean asynchronies were negative and rather small in the A_{full} condition, negative and relatively large in the A_{other} condition, and very small in the A_{self} condition. This pattern of results was observed in both Visual Feedback conditions. An ANOVA on these data (with the Greenhouse–Geisser correction applied when degrees of freedom exceeded one) revealed that the main effect of Auditory Feedback was statistically significant, $F(2, 46) = 29.81$, $p = .000$, whereas the Visual Feedback main effect and the Visual Feedback $\times$ Auditory Feedback interaction were not significant, $F(1, 23) = 0.07$, $p = .797$ and $F(2, 46) = 1.55$, $p = .244$,
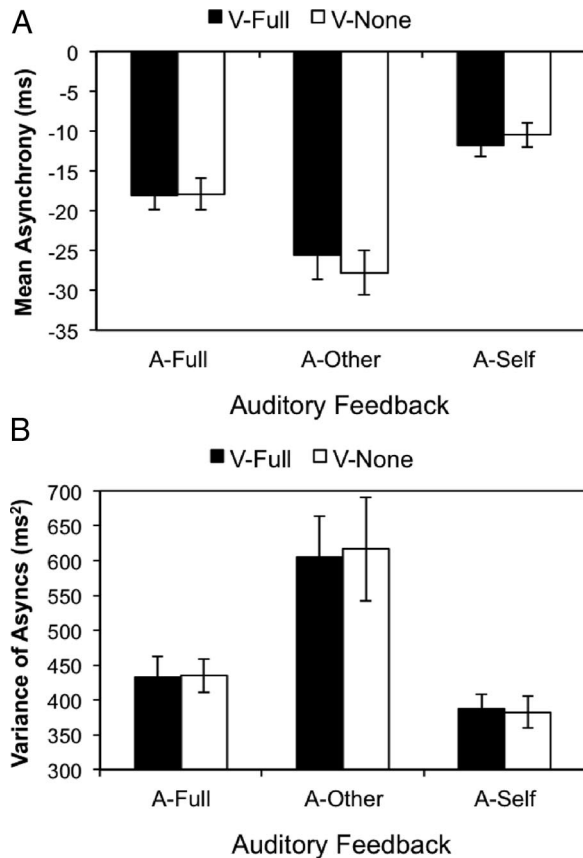
Figure 4. Mean asynchronies (panel A, in ms) and within-trial variance of asynchronies (panel B, in ms^2) averaged across participants for each combination of auditory feedback (A$_{full}$, A$_{other}$, A$_{self}$) and visual feedback (V$_{full}$, V$_{none}$) in Experiment 2. Error bars represent the standard error of the mean.

respectively. Pairwise comparisons of data from A$_{full}$, A$_{other}$, and A$_{self}$ conditions (collapsed across Visual Feedback) yielded significant differences for each comparison (Bonferroni-adjusted ps < .01). These results suggest that the beneficial effects of sounds triggered by taps on the accuracy of synchronization during paced dyadic alternation derive mainly from auditory feedback associated with the timing of one's own taps. Auditory feedback about the other's tap timing seems to dilute this benefit, whereas the presence or absence of visual feedback between coacting individuals has little effect on synchronization accuracy.

The variance of asynchronies was likewise affected by Auditory Feedback but not Visual Feedback. As can be seen in Figure 4B, the variability of asynchronies was lower in the A$_{self}$ condition than in the A$_{full}$ condition and, especially, the A$_{other}$ condition. An ANOVA yielded a significant effect of Auditory Feedback, $F(2, 46) = 12.08$, $p = .001$, whereas the Visual Feedback main effect and the Visual Feedback × Auditory Feedback interaction were not significant, $F(1, 23) = 0.02$, $p = .893$ and $F(2, 46) = 0.10$, $p = .887$, respectively. Pairwise comparisons of A$_{full}$, A$_{other}$, and A$_{self}$ data (collapsed across Visual Feedback) revealed significant differences for each comparison (Bonferroni-adjusted ps ≤ .05). Thus, the stability of synchronization during paced dyadic alter-

nation was decreased by auditory feedback about the timing of the other's taps. This apparent decrease in stability may, however, be a side effect of processes related to mutual adaptive timing, which we turn to next.

As in Experiment 1, mutual adaptive timing was assessed by measuring serial dependencies between asynchronies generated by the two individuals during paced dyadic alternation. Average joint lag 1 autocorrelation coefficients for the various Visual Feedback and Auditory Feedback conditions are displayed in Figure 5A. The first thing to note is that the autocorrelation coefficients in all conditions are positive and significantly greater than zero (ps < .05). Furthermore, the coefficients are highest in the A$_{full}$ condition, intermediate in the A$_{other}$ condition, and lowest in the A$_{self}$ conditions. This pattern of results holds for both Visual Feedback conditions. An ANOVA on these data returned a significant effect of Auditory Feedback, $F(2, 22) = 36.81$, $p = .000$; the Visual Feedback main effect and the Visual Feedback × Auditory Feedback interaction were not significant, $F(1, 11) = 0.74$, $p = .409$ and $F(2, 22) = 1.87$, $p = .182$, respectively. Pairwise comparisons of A$_{full}$, A$_{other}$, and A$_{self}$ conditions (collapsed across Visual Feedback) yielded significant differences for each comparison (Bonferroni-adjusted ps < .01).
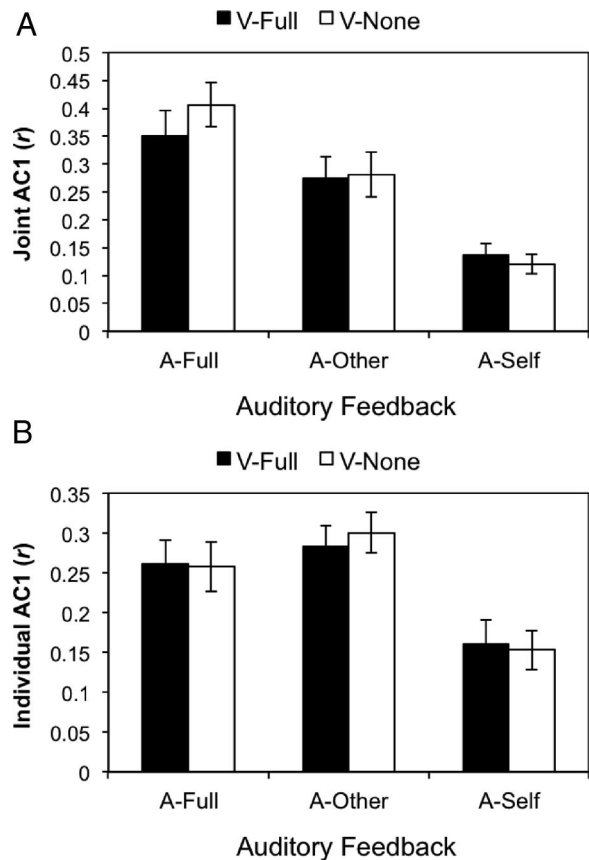

Figure 5. Average joint lag 1 autocorrelation (AC1) of asynchronies (panel A) and individual lag 1 autocorrelation of asynchronies (panel B) for each combination of auditory feedback (A$_{full}$, A$_{other}$, A$_{self}$) and visual feedback (V$_{full}$, V$_{none}$) (panel A) in Experiment 2. Error bars represent the standard error of the mean.

These results indicate that temporal assimilation occurred, and that it was strongest when each individual had access to auditory feedback about the timing of their own and their partner's taps. Interestingly, temporal assimilation was still present, in attenuated form, when individuals could hear sounds triggered by their partner's taps but not their own taps. This suggests that the perception of a partner's phase errors influences one's own tap timing, albeit relatively weakly, even in the absence of auditory feedback about the temporal relationship between one's own and the partner's taps. Joint lag 1 autocorrelation coefficients were also positive even when members of a dyad had access only to auditory feedback about their own taps. This effect cannot be due to mutual adaptive timing, as it occurred when the individuals neither heard nor saw their partner. The apparent serial dependencies between individuals' asynchronies under such conditions are most likely attributable to common cognitive–motor processes that introduce similarity in terms of autocorrelation structure into series of taps generated independently by different individuals. An example of such a process is phase drift, which may have several sources, including long-range temporal fluctuations associated with $1/f$ noise (Torres & Delignières, 2008).

Finally, our reexamination of potential effects of mutual adaptive timing on serial dependencies between each individual's own taps (indexed by individual lag 1 autocorrelations of asynchronies) yielded evidence for such influence. Averaged individual lag 1 autocorrelation coefficients are shown in Figure 5B. All coefficients are positive and significantly greater than zero ($ps < .05$). Moreover, individual lag 1 autocorrelation coefficients are higher in the A_{full} and A_{other} conditions than in the A_{self} condition. An ANOVA on these data indicated that the main effect of Auditory Feedback was significant, $F(2, 46) = 16.05$, $p = .000$, whereas the Visual Feedback main effect and the Visual Feedback × Auditory Feedback interaction were not significant, $F(1, 23) = 0.03$, $p = .855$ and $F(2, 46) = 0.22$, $p = .790$, respectively. Pairwise comparisons of data from A_{full}, A_{other}, and A_{self} conditions (collapsed across Visual Feedback) yielded significant differences for comparisons of A_{full} versus A_{self} and A_{other} versus A_{self} (Bonferroni-adjusted $ps < .01$) but not for A_{full} versus A_{other} ($p = .54$). These results suggest that access to auditory information about the timing of the other's taps affected serial dependencies between one's own taps. Specifically, the self-similarity between successive asynchronies produced by each individual was relatively high when he or she could hear sounds triggered by their partner's taps. This finding seems to be at odds with the results of Experiment 1 (although, as in the previous experiment, correlations between individual lag 1 autocorrelation coefficients were weak to moderate in the present experiment).

Although there are several differences in the designs of the two experiments (e.g., auditory feedback was treated as a between-participants factor in Experiment 1 and a within-participants factor in Experiment 2; Experiment 1 had a condition with no auditory feedback whereas Experiment 2 did not), two conditions are similar enough to be compared. These are the conditions in which (i) both members of a dyad could see and hear one another (i.e., the A_{full}/T_{joint} condition from Experiment 1 and the A_{full}/V_{full} condition from Experiment 2) and (ii) participants could see but not hear their partner (A_{full}/T_{solo} in Experiment 1 and A_{self}/V_{full} in Experiment 2). Visual inspection of the black-filled bars in Figure 3B (A_{full}/T_{joint} and T_{solo}) and Figure 5 (A_{full} and A_{self}/V_{full}) reveals

that individual lag 1 autocorrelation coefficients are commensurate across experiments when partners can see and hear one another (consider the leftmost black bars in the two figures), whereas this is not the case for conditions in which the only auditory feedback present is related to one's own taps (consider the rightmost black bars in the two figures).

The relatively low individual lag 1 autocorrelation coefficients observed when participants could not hear their partner in Experiment 2 may be a consequence of imagining sounds produced by the partner, as the individuals were knowingly engaged in dyadic tapping. According to this post hoc explanation, covert cognitive–motor processing associated with imagining sounds that occur in synchrony with the pacing events between one's own sounds may have reduced self-similarity between one's overt actions. Such imagery would be less likely in Experiment 1, as participants knowingly acted alone in the T_{solo} task (and, we may add, participants in the A_{none} group did not hear sounds triggered by taps at any stage of the experiment owing to the between-participants design).

Analysis of pooled data from Experiments 1 and 2. The positive values observed for joint lag 1 autocorrelation coefficients and individual lag 1 autocorrelation coefficients in Experiments 1 and 2 suggest that temporal assimilation may characterize serial dependencies in action timing at multiple levels during paced dyadic alternation. Specifically, assimilation may occur between coactors' alternating taps (interpersonal) and between one's own successive taps (intrapersonal). This raises the question of whether the processes underlying assimilation at these levels are linked. An analysis of pooled data from the conditions in which coactors could hear one another in Experiments 1 and 2 revealed that joint and individual lag 1 autocorrelation coefficients—each providing an index of assimilation strength[3]—were positively correlated across dyads ($r(23) = .646$, $p = .000$). Dyads displaying strong mutual temporal assimilation between coactors comprised individuals who each displayed relatively strong assimilation in the timing of their own successive actions. This finding indicates codependence of adaptive timing at the interpersonal and the intrapersonal level.

General Discussion

The current study investigated the dynamics of interpersonal mutual adaptive timing in a task that required paired musicians to tap their fingers in alternation with one another while maintaining synchrony with an isochronous auditory pacing signal. This paced dyadic alternation task was designed to approximate a subset of basic demands that arise when coordinating complementary musical parts with a rhythm section in an ensemble.

The analysis of serial dependencies in asynchronies between paired individuals' taps and the pacing tones revealed evidence for assimilation, more so than compensation, in the relative timing of the individuals' actions. Specifically, the positive lag 1 autocorrelation observed in the asynchrony series generated by alternating individuals indicated that, for example, if one individual produced a tap that was early relative to the target pacing event, then the next tap produced by the other individual tended to be early to a similar

---

[3] Individual lag 1 autocorrelation coefficients were averaged across members of a dyad.

degree. Although positive serial dependencies between asynchronies produced by two alternating individuals suggest that temporal assimilation eclipses interpersonal phase correction, they do not imply, however, that such phase correction was entirely absent. Indeed, phase correction has been found to occur even in response to temporal perturbations in unattended auditory streams (Repp, 2009), consistent with the notion that it is automatic and difficult to suppress.

By manipulating the availability of visual and auditory feedback about tap timing across our two experiments, it was shown that mutual temporal assimilation is strongest when auditory cues about each individual's actions are provided. That is, assimilation was stronger when individuals heard sounds triggered by their own and their partner's taps than when they heard sounds triggered only by their partner's taps. Auditory feedback—especially sounds triggered by one's own taps—also generally increased the accuracy (but not the stability) of dyadic sensorimotor synchronization, whereas the effects of visual feedback on mutual adaptive timing and synchronization accuracy were negligible.[4]

Overall, the current results suggest that mutual temporal assimilation during paced dyadic alternation is a consequence of perception–action links that support bidirectional interpersonal coupling in the auditory modality. In the following, we discuss (i) the relationship between temporal assimilation and error correction in interpersonal and intrapersonal adaptive timing, (ii) possible mechanisms underlying temporal assimilation, and (iii) the broader implications of our findings for interpersonal coordination during joint action in general and the specific case of ensemble music performance.

Temporal Assimilation and Error Correction

Our claim that the tendency for mutual temporal assimilation was stronger than the tendency for "temporal compensation" (i.e., each individual correcting for the phase error committed by the other individual on the previous tap) is based on the finding that the lag 1 autocorrelation for joint asynchrony series was positive rather than being at zero or negative in each of the two experiments. Positive serial dependencies were also found between each individual's own taps (i.e., individual lag 1 autocorrelations of asynchronies) during paced dyadic alternation in both experiments, and in solo tapping with every other tone of the pacing signal in Experiment 1.

Positive correlations between adjacent asynchronies are commonly observed in standard sensorimotor synchronization tasks where a single individual taps alone in time with a pacing signal. Under such circumstances, positive lag 1 autocorrelations can be attributed to various nonmutually exclusive sources, including local phase drift (Vorberg & Wing, 1996), the so-called "maintenance tendency" (i.e., the tendency to maintain a constant tapping period; Hary & Moore, 1987; Repp, 2011), and long-range serial correlations, such as 1/f noise (Torre & Delignières, 2008). These processes may be said to drive an intrapersonal form of temporal assimilation in the sense that they introduce self-similarity in the relative timing of an individual's successive taps.

Temporal assimilation may therefore characterize serial dependencies in action timing at multiple levels—between coactors' alternating taps (interpersonal) and between one's own successive taps (intrapersonal)—during paced dyadic alternation. Our analy-sis of pooled data from Experiments 1 and 2 in fact revealed that joint and individual lag 1 autocorrelation coefficients were positively correlated with one another across dyads. This suggests that processes underlying adaptive timing at the interpersonal and the intrapersonal level are linked.

Codependence of adaptive timing at multiple levels implies that processes associated with mutual adaptive timing at the interpersonal level may affect the operation of error-correction mechanisms that keep one's own actions synchronized with the pacing signal at the intrapersonal level. This question was addressed by examining the effects of coperformer presence (Experiment 1) and the availability of feedback (Experiment 2) on serial dependencies between each individual's own taps (i.e., individual lag 1 autocorrelations of asynchronies) during paced dyadic alternation.

In Experiment 1, positive serial dependencies between each individual's own taps were similar in magnitude for paced dyadic alternation and for solo tapping with every other tone of the pacing signal. By contrast, in Experiment 2, intrapersonal serial dependencies were lower (i.e., closer to zero) when each individual could not hear their partner during paced dyadic alternation than when auditory feedback about each other's tap timing was available. As pointed out in the Introduction, the lag 1 autocorrelation of asynchronies is known to approach zero as the gain of phase error correction is increased, and becomes negative when phase correction exceeds optimal values (see, e.g., Repp & Keller, 2008; Repp et al., 2012; Schulze & Vorberg, 2002). At first glance, then, our findings suggest that, although interpersonal temporal assimilation did not interfere with intrapersonal error correction in Experiment 1, it may have done so in Experiment 2.

This is unlikely to be the case, however, because individual lag 1 autocorrelation coefficients were relatively close to zero—which is indicative of effective phase correction—when individuals could not hear their partners in Experiment 2, but not during solo tapping in Experiment 1. This raises two possibilities: Either intrapersonal phase correction was especially active when paired individuals could not hear one another in Experiment 2, or processes that typically contribute to positive serial dependencies between an individual's taps were weakened in this condition. We favor the latter alternative because it is not obvious why the gain of phase correction should be heightened (via a presumably effortful process) solely owing to the fact that paired individuals cannot hear one another.

Thus, self-similarity between the timing of each individual's successive actions may have been reduced (resulting in lower individual lag 1 autocorrelations) when coactors could not hear each other in Experiment 2 owing to cognitive–motor processes associated with imagining the partner's intervening actions. Specifically, each individual may have simulated their partner's role in the paced dyadic alternation task (cf. Sebanz, Knoblich, Prinz, &

---

[4] As noted earlier, the positive lag 1 autocorrelations observed when co-actors could neither see nor hear one another in Experiment 2 may be artifacts related to similar, but possibly independent, long-range fluctuations in the timing of each individuals' movements (Torres & Delignières, 2008). Although such fluctuations are an interesting topic of investigation—for example, with regard to the functional relevance of 1/f noise in human cognition and action (see Chen, Ding, & Kelso, 1997; Delignières et al., 2006; Gilden, Thornton, & Mallon, 1995)—the time series generated in our tasks were not of sufficient length to analyze their fractal properties.

Wascher, 2006), and this simulation process may have affected their own action timing (see Jung et al., 2011, for a discussion of related issues in a nonrhythmic task). Although it is not presently known whether imagined actions influence serial dependencies between concurrently executed actions, studies requiring the mental subdivision of pacing intervals (Repp, 2011), and other work on trial-to-trial correlations in actual and imagined pointing movements (Valdez & Amazeen, 2010), suggest that this should not be ruled out.

Mechanisms Underlying Temporal Assimilation

Temporal assimilation at interpersonal and intrapersonal levels during paced dyadic alternation can be explained in accordance with concepts from dynamical systems theory and information processing approaches to rhythmic behavior. It is not our present purpose to adjudicate between these different frameworks (cf. Loehr, Large, & Palmer, 2011), but rather to illustrate how these two prominent approaches can accommodate our findings. Although the precise mechanisms behind mutual temporal assimilation are thus currently unclear, they may be elucidated in future work with computational models.

We start with a dynamical systems account. A parsimonious explanation of temporal assimilation can be provided by appealing to the dynamical systems concept of coupled oscillators instantiated in the coactors' nervous systems (see Oullier et al., 2008; Schmidt & Richardson, 2008). Dynamical approaches to rhythm perception and production (e.g., Large, 2008) postulate that the experience of pulse and meter arises when spontaneous oscillations in endogenous neural activity entrain to external rhythmic patterns. A sense of pulse (or beat) arises when neural oscillations become phase locked to a "preferred" level of periodicity in the external pattern, whereas hierarchical levels of pulsation and accents associated with meter stem from higher-order resonances that describe simple integer ratios in the oscillatory network (Iversen, Repp, & Patel, 2009; Large, 2000, 2008; Nozaradan, Peretz, Missal, & Moreaux, 2011).

In the context of our paced dyadic alternation task, it can be assumed that oscillators in each individual become entrained with the pacing signal and, potentially, with the coactor's actions. Specifically, oscillators may entrain (i) to the period of the pacing signal (resulting in the experience of pulse) and (ii) to a higher-order periodicity associated with the duple metric structure implied by a number of factors, including accents in the lead-in sequences, task instructions, and the requirement to tap on alternating beats of the pacing signal. Oscillators implicated in the latter level of entrainment presumably drive motor commands that trigger the finger taps of each individual. It can, furthermore, be assumed that these oscillators become coupled with one another across individuals in an antiphase relationship when coactors have access to information about each others' tap timing. This assumption is buttressed by previous research showing that interpersonal entrainment is difficult to resist during rhythmic tasks (e.g., pendulum-swinging or rocking in chairs) (Demos, Chaffin, Begosh, Daniels, & Marsh, 2012; Schmidt & O'Brien, 1997; Schmidt & Richardson, 2008).

Thus, paced dyadic alternation is characterized by two coupling collectives, one supporting in-phase coordination between each individual and the pacing signal, and the other supporting anti-

phase coordination between two coacting individuals. On this account, mutual temporal assimilation occurs owing to interactions between the two coupling collectives. Through such cross-talk—involving the exchange of information about the oscillators' relative phases and periods—the timing of in-phase coordination with the pacing signal affects the timing of antiphase coordination with the coactor, and vice versa. Each individual is thus sensitive to, and influenced by, the timing of his or her own taps and the other's taps, especially when these taps trigger salient distal effects in the form of sounds. Accordingly, as a consequence of antiphase interpersonal coupling, changes in the phase and/or period of the oscillator driven by perceptual input related to the other's tap timing nudge the oscillator driving one's own movement. Such interpersonal influences impact on each individual's in-phase coordination with the pacing signal, making the coactors' tap timing similar. In addition to this interpersonal assimilation, intrapersonal assimilation arises because the oscillator driving each individual's movements is also influenced by its recent history (a phenomenon known as hysteresis).

In sum, the above account postulates that temporal assimilation occurs at both the interpersonal and the intrapersonal level during paced dyadic alternation owing to the coupling of neural oscillators in two collectives. One collective is characterized by in-phase beat-based entrainment to the pacing signal, whereas the other involves antiphase coupling associated with the duple metric structure implied by the coactors' alternating movements. The proposal that mutual adaptive timing is based on information from multiple sources (interpersonal and intrapersonal) that are linked to different levels of a metric hierarchy is broadly consistent with recent claims that the control of movement timing during sensorimotor synchronization relies on multiple temporal references (Large, Fink, & Kelso, 2002; Repp, 2008, 2011).

An alternative to the above dynamical systems account of mutual temporal assimilation can be formulated in accordance with information-processing (specifically, discrete interval timing) approaches to the control of movement timing. Thus, it can be assumed that the timing of a sound produced by a coactor's tap, relative to the nearest pacing signal tone, is treated by one's action control system as a temporal target for one's own subsequent tap. In other words, the coactor's tap may serve as a temporal reference for phase resetting, in a similar fashion to how the tones of out-of-phase distracter sequences that are interleaved with a target pacing signal tend to attract taps during solo sensorimotor synchronization (Repp, 2004). The control system may thus aim to produce taps at a fixed time interval—dictated by the target tempo—following a coactor's sound (or following a virtual time point located between the coactor's sound and the relevant pacing tone). This tendency could be related to the tendency for coactors to copy each others' intertap intervals during in-phase dyadic synchronization in the absence of an external pacing signal (Konvalinka et al., 2010; Merker et al., 2009). In any case, an interval-based conceptualization is intuitively appealing because it is not tied to a particular mode of interpersonal coupling (e.g., antiphase), and it therefore seems well suited to account for the variety of interlocking rhythm patterns that characterize pieces of ensemble music. This account is also generally consistent with the notion that coactors use information about each other's movement timing as reference points for joint anticipatory control (Knoblich & Jordan, 2003).

Implications for Joint Action and Ensemble Performance

The finding that mutual adaptive timing is characterized by interpersonal temporal assimilation at the millisecond timescale has implications for understanding the mechanisms by which multiple individuals coordinate their movements during rhythmically structured, complementary joint action (see Knoblich, Butterfill, & Sebanz, 2011). A noteworthy implication is that temporal assimilation under such circumstances may facilitate real-time interpersonal coordination via similar mechanisms to those that mediate other forms of behavioral assimilation, in particular, imitation and nonconscious mimicry.

Imitation and mimicry generally entail one individual matching the spatiotemporal features of another's movements or their effects (see Brass & Heyes, 2005; Zentall, 2006). Such behavioral matching, which can occur automatically and without conscious awareness, may function multifariously to facilitate skill acquisition, social learning, and interpersonal bonding (Lakin, Jefferis, Cheng, & Chartrand, 2003; Zentall, 2006). Behavioral assimilation in the temporal domain—as observed in the current study for asynchronies during externally paced dyadic alternation and in other studies for intertap intervals during self-paced dyadic synchronization (Konvalinka et al., 2010; Merker et al., 2009)—may be particularly relevant to the formation and tightening of interpersonal bonds. Indeed, Hove and Risen (2009) have demonstrated that interpersonal synchrony promotes feelings of affiliation, possibly by blurring the distinction between self and other (see Gallese, 2003). To the extent that mutual temporal assimilation assists multiple individuals to act as one, it may thus strengthen interpersonal affiliation and group cohesion. Temporal assimilation may thus have benefits that extend beyond basic temporal coordination into the social sphere.

Our findings are, however, most clearly relevant to the specific case of interpersonal coordination in musical ensemble performance. We observed that interpersonal temporal assimilation was strongest when coacting individuals' finger taps triggered sounds. The presence or absence of visual feedback between the individuals, by contrast, had no discernable effect upon mutual adaptive timing. These results suggest that interpersonal temporal assimilation was mediated primarily by perception–action coupling in the auditory modality. Musical ensemble performance is a domain where interpersonal coordination relies more crucially on auditory than visual information (Goebl & Palmer, 2009; Keller & Appel, 2010). Based on the current findings, we propose that mutual temporal assimilation may facilitate basic ensemble coherence by increasing the similarity of coperformers' productions, thereby assisting multiple individuals to sound collectively as one. In musical contexts characterized by expressively motivated timing deviations, such similarity may enhance stylistic compatibility among coperformers and thus facilitate the interpersonal coordination of expressive performance parameters. Stylistic compatibility may also be beneficial to the extent that it allows coperformers to simulate, and thereby predict, the timing of each other's upcoming actions accurately (Keller et al., 2007; Pecenka & Keller, 2011).

The above view of interpersonal coordination in ensemble performance implies that mutual adaptive timing is not simply a matter of temporal compensation (e.g., local asynchrony reduction), but also involves behavioral assimilation that may be related to the more general tendency toward automatic mimicry and imitation. Precise yet flexible coordination in musical ensembles may thus be achieved via similar mechanisms to those that regulate real-time interpersonal dynamics in joint action more broadly. However, in musical contexts, mutual temporal assimilation may rely on fast-acting auditory–motor links to a greater degree than on processes that guide visually mediated mimicry at longer timescales.

References

Aschersleben, G. (2002). Temporal control of movements in sensorimotor synchronization. *Brain and Cognition, 48,* 66–79. doi:10.1006/brcg.2001.1304

Aschersleben, G., & Prinz, W. (1995). Synchronizing actions with events: The role of sensory information. *Perception & Psychophysics, 57,* 305–317. doi:10.3758/BF03213056

Brass, M., & Heyes, C. (2005). Imitation: Is cognitive neuroscience solving the correspondence problem? *Trends in Cognitive Sciences, 9,* 489–495. doi:10.1016/j.tics.2005.08.007

Brendel, A. (2007). *Alfred Brendel on music: His collected essays.* London, UK: JR Books.

Chartrand, T. L., & Bargh, J. A. (1999). The chameleon effect: The perception-behavior link and social interaction. *Journal of Personality and Social Psychology, 76,* 893–910. doi:10.1037/0022-3514.76.6.893

Chartrand, T. L., Maddux, W., & Lakin, J. (2005). Beyond the perception-behavior link: The ubiquitous utility and motivational moderators of nonconscious mimicry. In R. Hassin, J. Uleman, & J. A. Bargh (Eds.), *The new unconscious* (pp. 334–361). New York: Oxford University Press.

Chen, Y., Ding, M., & Kelso, J. A. S. (1997). Long memory processes (1/f - type) in human coordination. *Physical Review Letters, 79,* 4501–4504. doi:10.1103/PhysRevLett.79.4501

Delignières, D., Ramdani, S., Lemoine, L., Torre, K., Fortes, M., & Ninot, G. (2006). Fractal analysis for short time series: A reassessment of classical methods. *Journal of Mathematical Psychology, 50,* 525–544. doi:10.1016/j.jmp.2006.07.004

De Maeght, S., & Prinz, W. (2004). Action induction through action observation. *Psychological Research, 68,* 97–114. doi:10.1007/s00426-003-0148-3

Demos, A. P., Chaffin, R., Begosh, K. T., Daniels, J. R., & Marsh, K. L. (2012). Rocking to the beat: Effects of music and partner's movements on spontaneous interpersonal coordination. *Journal of Experimental Psychology: General, 141,* 49–53. doi:10.1037/a0023843

Gallese, V. (2003). The roots of empathy: The shared manifold hypothesis and the neural basis of intersubjectivity. *Psychopathology, 36,* 171–180. doi:10.1159/000072786

Gallese, V., Keysers, C., & Rizzolatti, G. (2004). A unifying view of the basis of social cognition. *Trends in Cognitive Sciences, 8,* 396–403. doi:10.1016/j.tics.2004.07.002

Gilden, D. L., Thornton, T., & Mallon, M. W. (1995). 1/f noise in human cognition. *Science, 267,* 1837–1839. doi:10.1126/science.7892611

Goebl, W., & Palmer, C. (2009). Synchronization of timing and motion among performing musicians. *Music Perception, 26,* 427–438. doi:10.1525/mp.2009.26.5.427

Hary, D., & Moore, G. P. (1987). Synchronizing human movement with an external clock source. *Biological Cybernetics, 56,* 305–311. doi:10.1007/BF00319511

Hove, M. J., & Risen, J. L. (2009). It's all in the timing: Interpersonal synchrony increases affiliation. *Social Cognition, 27,* 949–961. doi:10.1521/soco.2009.27.6.949

Iversen, J. R., Repp, B. H., & Patel, A. D. (2009). Top-down control of rhythm perception modulates early auditory responses. *Annals of the*

New York Academy of Sciences, 1169, 58–73. doi:10.1111/j.1749-6632.2009.04579.x

Jeannerod, M. (2006). *Motor cognition: What actions tell the self.* Oxford, UK: Oxford University Press. doi:10.1093/acprof:oso/9780198569657.001.0001

Jung, C., Holländer, A., Müller, K., & Prinz, W. (2011). Sharing a bimanual task between two: Evidence of temporal alignment in interpersonal coordination. *Experimental Brain Research, 211,* 471–482. doi:10.1007/s00221-011-2665-4

Keller, P. E. (2008). Joint action in music performance. In F. Morganti, A. Carassa, & G. Riva (Eds.), *Enacting intersubjectivity: A cognitive and social perspective on the study of interactions* (pp. 205–221). Amsterdam: IOS Press.

Keller, P. E., & Appel, M. (2010). Individual differences, auditory imagery, and the coordination of body movements and sounds in musical ensembles. *Music Perception, 28,* 27–46. doi:10.1525/mp.2010.28.1.27

Keller, P. E., Knoblich, G., & Repp, B. H. (2007). Pianists duet better when they play with themselves: On the possible role of action simulation in synchronization. *Consciousness and Cognition, 16,* 102–111. doi:10.1016/j.concog.2005.12.004

Kelso, J. A. S., DelColle, J., & Schöner, G. (1990). Action-perception as a pattern formation process. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 139–169). Hillsdale, NJ: Erlbaum.

Knoblich, G., Butterfill, S., & Sebanz, N. (2011). Psychological research on joint action: Theory and data. In B. Ross (Ed.), *The psychology of learning and motivation* (Vol. 54, pp. 59–101), Burlington: Academic Press.

Knoblich, G., & Jordan, S. (2002). The mirror system and joint action. In M. I. Stamenov & V. Gallese (Eds.), *Mirror neurons and the evolution of brain and language* (pp. 115–124). Amsterdam, The Netherland: John Benjamins.

Knoblich, G., & Jordan, S. (2003). Action coordination in groups and individuals: Learning anticipatory control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 1006–1016. doi:10.1037/0278-7393.29.5.1006

Knoblich, G., & Sebanz, N. (2008). Evolving intentions for social interaction: From entrainment to joint action. *Philosophical Transactions of the Royal Society B, 363,* 2021–2031. doi:10.1098/rstb.2008.0006

Konvalinka, I., Vuust, P., Roepstorff, A., & Frith, C. D. (2010). Follow you, follow me: Continuous mutual prediction and adaptation in joint tapping. *The Quarterly Journal of Experimental Psychology, 63,* 2220–2230. doi:10.1080/17470218.2010.497843

Lakin, J. L., Jefferis, V. E., Cheng, C. M., & Chartrand, T. L. (2003). The chameleon effect as social glue: Evidence for the evolutionary significance of nonconscious mimicry. *Journal of Nonverbal Behavior, 27,* 145–162. doi:10.1023/A:1025389814290

Large, E. W. (2000). On synchronizing movements with music. *Human Movement Science, 19,* 527–566. doi:10.1016/S0167-9457(00)00026-9

Large, E. W. (2008). Resonating to musical rhythm: Theory and experiment. In S. Grondin (Ed.), *The psychology of time* (pp. 189–231). West Yorkshire: Emerald.

Large, E. W., Fink, P., & Kelso, J. A. S. (2002). Tracking simple and complex sequences. *Psychological Research, 66,* 3–17. doi:10.1007/s004260100069

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review, 106,* 119–159. doi:10.1037/0033-295X.106.1.119

Loehr, J. D., Large, E. W., & Palmer, C. (2011). Temporal coordination and adaptation to rate change in music performance. *Journal of Experimental Psychology: Human Perception and Performance, 37,* 1292–1309. doi:10.1037/a0023102

London, J. (2004). *Hearing in time: Psychological aspects of musical meter.* Oxford: Oxford University Press.

Maduell, M., & Wing, A. M. (2007). The dynamics of ensemble: The case for flamenco. *Psychology of Music, 35,* 591–627. doi:10.1177/0305735607076446

Mates, J. (1994). A model of synchronization of motor acts to a stimulus sequence: Part I. Timing and error corrections. *Biological Cybernetics, 70,* 463–473. doi:10.1007/BF00203239

Mates, J., Radil, T., & Pöppel, E. (1992). Cooperative tapping: Time control under different feedback conditions. *Perception and Psychophysics, 52,* 691–704. doi:10.3758/BF03211706

Merker, B. H., Madison, G., & Eckerdal, P. (2009). On the role and origin of isochrony in human rhythmic entrainment. *Cortex, 45,* 4–17. doi:10.1016/j.cortex.2008.06.011

Nowicki, D. L. (2009). *Shared clocks: Investigating interpersonal sensorimotor synchronization* (Doctoral dissertation). Leipzig: University of Leipzig.

Nozaradan, S., Peretz, I., Missal, M., & Mouraux, A. (2011). Tagging the neuronal entrainment to beat and meter. *The Journal of Neuroscience, 31,* 10234–10240. doi:10.1523/JNEUROSCI.0411-11.2011

Oullier, O., de Guzman, G. C., Jantzen, K. J., Lagarde, J., & Kelso, J. A. S. (2008). Social coordination dynamics: Measuring human bonding. *Social Neuroscience, 3,* 178–192. doi:10.1080/17470910701563392

Overy, K., & Molnar-Szakacs, I. (2009). Being together in time: Musical experience and the mirror neuron system. *Music Perception, 26,* 489–504. doi:10.1525/mp.2009.26.5.489

Pecenka, N., & Keller, P. E. (2011). The role of temporal prediction abilities in interpersonal sensorimotor synchronization. *Experimental Brain Research, 211,* 505–515. doi:10.1007/s00221-011-2616-0

Pressing, J. (1998). Error correction processes in temporal pattern production. *Journal of Mathematical Psychology, 42,* 63–101. doi:10.1006/jmps.1997.1194

Prinz, W., Aschersleben, G., & Koch, I. (2009). Cognition and action. In E. Morsella, J. Bargh, & P. M. Gollwitzer (Eds.), *The psychology of action* (Vol. 2: Mechanisms of human action, pp. 35–71). Oxford, UK: Oxford 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). Oxford, UK: Clarendon Press.

Repp, B. H. (2004). On the nature of phase attraction in sensorimotor synchronization with interleaved auditory sequences. *Human Movement Science, 23,* 389–413. doi:10.1016/j.humov.2004.08.014

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review, 12,* 969–992. doi:10.3758/BF03206433

Repp, B. H. (2006). Musical synchronization. In E. Altenmüller, M. Wiesendanger, & J. Kesselring (Eds.), *Music, motor control, and the brain.* Oxford, UK: Oxford University Press. doi:10.1093/acprof:oso/9780199298723.003.0004

Repp, B. H. (2008). Multiple temporal references in sensorimotor synchronization with metrical auditory sequences. *Psychological Research, 72,* 79–98. doi:10.1007/s00426-006-0067-1

Repp, B. H. (2009). Rhythmic sensorimotor coordination is resistant but not immune to auditory stream segregation. *Quarterly Journal of Experimental Psychology, 62,* 2306–2312.

Repp, B. H. (2011). Temporal evolution of the phase correction response in synchronization with perturbed two-interval rhythms. *Experimental Brain Research, 208,* 89–101. doi:10.1007/s00221-010-2462-5

Repp, B. H., & Keller, P. E. (2008). Sensorimotor synchronization with adaptively timed sequences. *Human Movement Science, 27,* 423–456. doi:10.1016/j.humov.2008.02.016

Repp, B. H., Keller, P. E., & Jacoby, N. (2012). Quantifying phase correction in sensorimotor synchronization: Empirical comparison of three paradigms. *Acta Psychologica, 139,* 281–290. doi:10.1016/j.actpsy.2011.11.002

Repp, B. H., & Penel, A. (2002). Auditory dominance in temporal processing: New evidence for synchronization with simultaneous visual and auditory sequences. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1085–1099. doi:10.1037/0096-1523.28.5.1085

Richardson, M. J., Marsh, K. L., & Schmidt, R. C. (2005). Effects of visual and verbal information on unintentional interpersonal coordination. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 62–79. doi:10.1037/0096-1523.31.1.62

Rizzolatti, G., & Sinigaglia, C. (2010). The functional role of the parieto-frontal mirror circuit: Interpretations and misinterpretations. *Nature Reviews Neuroscience, 11,* 264–274. doi:10.1038/nrn2805

Schmidt, R. C., & O'Brien, B. (1997). Evaluating the dynamics of unintended interpersonal coordination. *Ecological Psychology, 9,* 189–206. doi:10.1207/s15326969eco0903_2

Schmidt, R. C., & Richardson, M. J. (2008). Dynamics of interpersonal coordination. In A. Fuchs & V. K. Jirsa (Eds.), *Coordination: Neural, behavioral and social dynamics* (pp. 281–307). Berlin: Springer-Verlag. doi:10.1007/978-3-540-74479-5_14

Schögler, B. (1999–2000). Studying temporal co-ordination in jazz duets [Special Issue]. *Musicae Scientiae, 1999*–2000, 75–91.

Schöner, G. (2002). Timing, clocks, and dynamical systems. *Brain and Cognition, 48,* 31–51. doi:10.1006/brcg.2001.1302

Schulze, H.-H., & Vorberg, D. (2002). Linear phase correction models for synchronization: Parameter identification and estimation of parameters. *Brain and Cognition, 48,* 80–97. doi:10.1006/brcg.2001.1305

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. *Trends in Cognitive Sciences, 10,* 70–76. doi:10.1016/j.tics.2005.12.009

Sebanz, N., Knoblich, G., & Prinz, W. (2005). How to share a task: Core presenting stimulus-response mappings. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 1234–1246. doi:10.1037/0096-1523.31.6.1234

Sebanz, N., Knoblich, G., Prinz, W., & Wascher, E. (2006). Twin Peaks: An ERP study of action planning and control in co-acting individuals. *Journal of Cognitive Neuroscience, 18,* 859–870. doi:10.1162/jocn.2006.18.5.859

Semjen, A., & Schulze, H.-H., & Vorberg, D. (2000). Timing precision in continuation and synchronization tapping. *Psychological Research, 63,* 137–147. doi:10.1007/PL00008172

Shockley, K., Santana, M., & Fowler, C. A. (2003). Mutual interpersonal postural constraints are involved in cooperative conversation. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 326–332. doi:10.1037/0096-1523.29.2.326

Torre, K., & Delignières, D. (2008). Unraveling the finding of $1/f^\beta$ noise in self-paced and synchronized tapping: A unifying mechanistic model. *Biological Cybernetics, 99,* 159–170. doi:10.1007/s00422-008-0247-8

Valdez, A. B., & Amazeen, E. L. (2010). Motor imagery may incorporate trial-to-trial error. *Journal of Motor Behavior, 42,* 241–256. doi:10.1080/00222895.2010.497511

Vlainic, E., Liepelt, R., Colzato, L. S., Prinz, W., & Hommel, B. (2010). The virtual co-actor: The Social Simon effect does not rely on online feedback from the other. *Frontiers in Psychology, 1,* 1–6. doi:10.3389/fpsyg.2010.00208

Vorberg, D., & Schulze, H. H. (2002). Linear phase-correction in synchronization: Predictions, parameter estimation, and simulations. *Journal of Mathematical Psychology, 46,* 56–87. doi:10.1006/jmps.2001.1375

Vorberg, D., & Wing, A. M. (1996). Modeling variability and dependence in timing. In H. Heuer & S. W. Keele (Eds.), *Handbook of perception and action: Motor skills*. San Diego, CA: Academic Press. doi:10.1016/S1874-5822(06)80007-1

Wilson, M., & Knoblich, G. (2005). The case for motor involvement in perceiving conspecifics. *Psychological Bulletin, 131,* 460–473. doi:10.1037/0033-2909.131.3.460

Wing, A. M. (2002). Voluntary timing and brain function: An information processing approach. *Brain and Cognition, 48,* 7–30. doi:10.1006/brcg.2001.1301

Zentall, T. R. (2006). Imitation: Definitions, evidence, and mechanisms. *Animal Cognition, 9,* 335–353. doi:10.1007/s10071-006-0039-2

Zwickel, J., & Prinz, W. (2012). Assimilation and contrast: The two sides of specific interference between action and perception. *Psychological Research, 76,* 171–182. doi:10.1007/s00426-011-0338-3

E-Mail Notification of Your Latest Issue Online!

Would you like to know when the next issue of your favorite APA journal will be available online? This service is now available to you. Sign up at http://notify.apa.org/ and you will be notified by e-mail when issues of interest to you become available!