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Follow you, follow me: Continuous mutual prediction and adaptation in joint tapping

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Follow you, follow me: Continuous mutual prediction and adaptation in joint tapping

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To study the mechanisms of coordination that are fundamental to successful interactions we carried out a joint finger tapping experiment in which pairs of participants were asked to maintain a given beat while synchronizing to an auditory signal coming from the other person or the computer. When both were hearing each other, the pair became a coupled, mutually and continuously adaptive unit of two "hyper-followers", with their intertap intervals (ITIs) oscillating in opposite directions on a tap-to-tap basis. There was thus no evidence for the emergence of a leader–follower strategy. We also found that dyads were equally good at synchronizing with the irregular, but responsive other as with the predictable, unresponsive computer. However, they performed worse when the "other" was both irregular and unresponsive. We thus propose that interpersonal coordination is facilitated by the mutual abilities to (a) predict the other's subsequent action and (b) adapt accordingly on a millisecond timescale.

Keywords: Interpersonal coordination; Tapping; Prediction; Adaptation.

Human beings have an extraordinary ability to align their goals, intentions, and actions in order to achieve highly flexible interactions (Newman-Norlund, Noordzij, Meulenbroek, & Bekkering, 2007). Whether engaging in a discussion with others, performing in a symphony orchestra, dancing tango, or working together towards simpler goal-directed tasks, people are capable of coordinating their movements with one another quickly and with little apparent conscious effort.

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However, the behavioural and neural processes underlying this coordinated behaviour are still poorly understood (Sebanz, Bekkering, & Knoblich, 2006), particularly the mechanisms allowing people to coordinate on a millisecond timescale. The goal of our study was to explore the ongoing behavioural dynamics that result from a coordinated joint tapping task in different auditory feedback settings. We hypothesize that human interaction involves highly adaptable, coordinated activation of biological subsystems within and between individuals and that these become coupled to each other as a result of the interaction (de Rugy, Salesse, Oullier, & Temprado, 2006; Knoblich & Sebanz, 2008; Oullier, De Guzman, Jantzen, Lagarde, & Kelso, 2008; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990; Schmidt & Richardson, 2008) even at a very short timescale.

Joint coordinated behaviour has commonly been studied from the dynamical systems perspective in the context of intra- and interpersonal synchronization, looking at the emergent dynamical properties of synchronized walking (van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008), postural sway (Shockley, Santana, & Fowler, 2003), and the swinging of limbs (Mottet, Guiard, Ferrand, & Bootsma, 2001; Schmidt et al., 1990). Dyads have been found to synchronize their movements together when walking side by side, or when immersed in conversation with one another. Synchronization has also been investigated and found in less pragmatic actions, such as with dyads rocking side by side in rocking chairs (Richardson et al., 2007) as well as entraining when swinging pendulums together (Schmidt et al., 1998), even in the absence of instructions to synchronize (Oullier et al., 2008; Richardson, Marsh, & Schmidt, 2005; Schmidt & O'Brien, 1997). Additionally, Richardson et al. found that people synchronized their rocking even when the natural frequencies of their chairs were different, showing that people try to synchronize even against the natural tendency of the dynamical system. Another major finding, which has been a basis of existing dynamical systems models of coordination, has shown that two stable dominant modes (Haken, Kelso, & Bunz, 1985), in-phase and antiphase synchronization, corresponding to movement in the same and opposite directions, respectively, emerge in both intra- and interpersonal temporal coordination (Schmidt & Richardson, 2008). In other words, people coordinate their movements according to dynamical system principles of coupled oscillators, such that their limbs tend to be simultaneously at the same spot in their cycles or in opposite spots. This finding has provided a basis for modelling interpersonal coordination; however, what does this imply regarding social behaviour? More specifically, does one system more strongly lead the other towards these stable states, or do they mutually adapt in order to swing in phase and antiphase? Also, can we learn more about this process by looking at what happens on a short millisecond timescale?

A second approach to studying interpersonal coordination has examined social implications of synchronization, mostly centred on observations that performing similar and/or coordinated actions strengthens rapport and social bond among people, both with nonconscious mimicry of others' behaviour (Chartland & Bargh, 1999) and with mutual coordination of actions as has been shown in parent–child bonding (Isabella, Belsky, & van Eye, 1989) and student–teacher relations (Bernieri, 1988; LaFrance, 1979). It has also been demonstrated that when people act in synchrony with others, they subsequently adopt more cooperative behaviour (van Baaren, Holland, Kawakami, & van Knippenberg, 2004; Wiltermuth & Heath, 2009), and increased feelings of rapport have even been shown to correlate with the two stable modes of synchrony (Miles, Nind, & Macrae, 2009). In cases of "action similarity", such as with the chameleon effect, increased rapport may be due to a matching of actions performed (Chartland & Bargh, 1999). The positive relationship between social bonding and temporal synchronization involving accuracy in timing has been suggested to be due to a weakening of boundaries between the self and other, which leads to increased affiliation effects (Hove, 2008), or a facilitation of information flow and thus knowledge transmission between people (Wilson, 2001). Although we do not explore the relationship between social rapport and synchronization in this paper, it will be relevant to our future work.

While much research has been done on the properties and social implications of synchronization, existing models of interpersonal coordination do not assess the directionality of the interaction on a short timescale in real time. In order to study this phenomenon, we designed a joint, coordinated finger-tapping paradigm. Previous research has extensively explored finger tapping from the perspective of sensorimotor synchronization (Repp, 2005) looking at isochronous self-paced tapping (Wing & Kristofferson, 1973), as well as synchronization with a computer-generated metronome (Repp & Keller, 2008; Vorberg & Schulze, 2002) or with piano recordings of self and other (Keller, Knoblich, & Repp, 2007). However, beat keeping and rhythm production are rarely done in isolation or with a nonresponsive partner, and joint coordination of perception and action between pairs tapping together has yet to be explored. We chose this paradigm because it permits various conditions of interaction that we could easily manipulate experimentally to address the issue of directionality of coupling between pairs of participants in various coupling conditions.

We set up an experiment in which pairs were coupled through their headphones, and the amount of shared information was controlled for, as we were interested in capturing the online tapping dynamics of dyads in various degrees of interaction: no mutual coordination (but to a steady beat), and unidirectional and bidirectional coordination. These conditions were constrained by the experimenter in the degree of auditory coupling, such that participants found themselves in scenarios where they could hear only themselves tapping, only the other, or the computer metronome. We were interested in studying the mechanisms people use to keep the given beat alone versus with another person or the computer and how well they are able to synchronize. We aimed to investigate whether a leader–follower relationship would emerge automatically, such that Participant A keeps the given beat, and B synchronizes with A, or whether participants would mutually follow each other without a clear leader in place. We expected clearer leader–follower patterns to emerge when the coupling was unidirectional (one-way interaction) than when it was bidirectional (two-way interaction). We also predicted that participants would be better at synchronizing with the steady computer-generated beat than with the other person who is irregular.

Method

Participants

Right-handed participants with normal hearing were recruited from the University of Aarhus, Denmark. A total of 32 paid volunteers (21 females, 11 males; mean age = 27.3 years) participated in the study. The participants were paired off at random, comprising 16 pairs (both same and mixed-gender).

Materials and apparatus

Two Yamaha MIDI keyboards with weighted keys were connected to the computer via an M-Audio 2 × 2 MIDISPORT interface. The MIDI outs sent signals to two respective channels on a Phonic mixer via two Roland JV-1010 sound modules. The stimulus was an 8-beat metronome, generated using Cubase (2009), a computer program for music recording and production. The signal was sent from the computer, fed through the mixer, and received at two sets of headphones. The output from the keyboards was recorded in real time in Cubase. The mixer was used to adjust the auditory feedback that the participants were receiving—namely, hearing the computer-generated metronome, their own feedback from the key presses, or their partner's feedback. The elaborate set-up ensured an auditory delay (time between pressing the key and hearing the sound) of no more than 6 ms.

Task and procedure

The members of each pair were placed in separate rooms, receiving no visual contact with each other. They were asked to tap on their respective keyboards for 8 bars (32 beats) by pressing the key corresponding to notes C3 and E3, respectively, with their right index finger, following the 8-beat stimulus sent through their headphones. Two different notes were chosen so that the participants would identify the sounds as coming from the self or other, respectively. The stimulus was a metronome, with a tempo of 96, 120, or 150 beats per minute (bpm). Each trial was initiated by 8 beats at one of the three tempos, which were randomly ordered. Following the 8 beats, the stimulus would cease, and the participant would receive auditory feedback from one of three sources: their own tapping, their partner's tapping, or the computer metronome. The participants found themselves in one of four different scenarios: (a) computer condition—both participants only hear computer-generated beats; (b) uncoupled condition—both participants only hear self-generated beats; (c) unidirectional coupling—both participants only hear beats generated by (ii) Participant 1 or (ii) Participant 2; and (d) bidirectional coupling—both participants only hear beats generated by the other participant. Each condition was carried out four times for each tempo, resulting in a total of 60 trials per pair.

Two instructions were given to the participants: to keep the given beat as precisely as possible, while at the same time synchronizing with the other member or the computer metronome in scenarios corresponding to hearing the other member or the computer, respectively. Therefore, they were informed that they would be assessed on both synchronization and drift from the metronome. The participants were individually told whom they would be hearing prior to each trial.

Data analysis

The data were imported into MATLAB using the MIDI toolbox (Eerola & Toiviainen, 2004), and only the onset tapping times were analysed. One pair's data were discarded because of a participant who was not alert during the study. Three types of analyses were computed—namely, windowed cross correlations, synchronization indices, and the means of the absolute difference between the intertap interval (ITI) of each member and the target metronome.

Windowed cross correlations between the two time series corresponding to the dyads' ITIs were computed for each condition, using a moving window size of 6 taps, a maximum lag of 3, and a window and lag increment of 1. Cross correlation analysis and many other methods assume that two time series are stationary. Stationary processes have a stable structure over time, with constant mean, variance, and other statistical properties (Boker, Xu, Rotondo, & King, 2002). Rather than assuming stationarity over the entire time series, this analysis enabled us to treat the time series as only having local stationarity, by using short durations of data to estimate the lag and variability of association between the two members of a pair and how they change over time (Boker et al., 2002). Four trials were collected for each condition of interaction, and the correlation coefficients for lag -1, 0, and $+1$ were computed between the participants' ITIs across these short intervals of time and were averaged per condition for each pair. The coefficients (transformed into Fisher z scores) were compared across interaction conditions for each tempo using a 2×2 multivariate analysis of variance (MANOVA), with auditory feedback of Member 1 (M1) and Member 2 (M2) as the factors (i.e., hearing self or other) and lag -1, 0, and $+1$ correlation coefficients as the dependent variables. This analysis gave an indication of the directionality of the interaction—namely, whether the participants were not interacting with each other (i.e., uncorrelated), or whether there was a clear leader–follower dynamic where one participant led the other towards their own tempo, or whether the adjustment of ITIs was mutual. For example, a positive lag -1 correlation alone would indicate a leader–follower dynamic such that one member (M1) is one tap behind the other; similarly, a positive lag $+1$ correlation would indicate the other member (M2) as the follower; a positive lag 0 correlation would mean that the participants are correlated in real time; finally, a negative lag 0 correlation would mean that the two participants are anticorrelated, either mutually or individually (depending on the lag 1 coefficients) following the other member of the pair.

In order to address task performance, we looked both at how well the participants were able to synchronize and to keep the given beat. Synchronization indices based on variance of relative phase (Mardia & Jupp, 2000) were calculated for each participant in relation to the computer or the other member. The index is a unitless number, which ranges from 0 to 1, representing the absence of synchronization and perfect synchrony, respectively. An index greater than .73 has been considered as indicating the synchronization regime (Tognoli, Lagarde, DeGuzman, & Kelso, 2007). The indices were compared across the following three conditions using a one-way analysis of variance (ANOVA): computer condition, looking at the relative phase between each member and the metronome; the unidirectional coupling condition, taking the relative phase between the two members of the dyad; and the bidirectional coupling condition.

In order to evaluate how well people were able to keep the given beat, we looked at the means of the absolute difference between the ITI of each member and the target metronome. We compared the conditions for each tempo using a 2 × 2 ANOVA, where the factors were the self and the other's auditory feedback (i.e., each hearing self or other).

Results

Windowed cross-correlations of intertap intervals

Windowed cross-correlations of the dyads' intertap intervals were computed for the 15 pairs. The 2 × 2 design is shown in Figure 1a, along with an example of trials for one pair of participants (Figure 1b–1e). The pattern of results was very similar for all three tempi. The means and standard errors of the cross-correlation coefficients are summarized in Figure 2 for a tempo of 96 bpm.

As can be seen in Figure 2, when members could only hear themselves, there were no correlations. In the unidirectional coupling condition, there was a small but significant negative correlation at lag zero and larger positive correlations at lag 1 (lag −1 when both are hearing Member 1 and lag +1 when both are hearing Member 2). In the bidirectional coupling condition, both members showed the "follower pattern" (positive lag 1 correlation and negative lag 0) with positive correlations at both lag −1 and +1 and an even greater negative correlation at lag 0, confirmed by a significant interaction for tempi 96 and 150 bpm. The significance of these various effects is shown in Table 1.

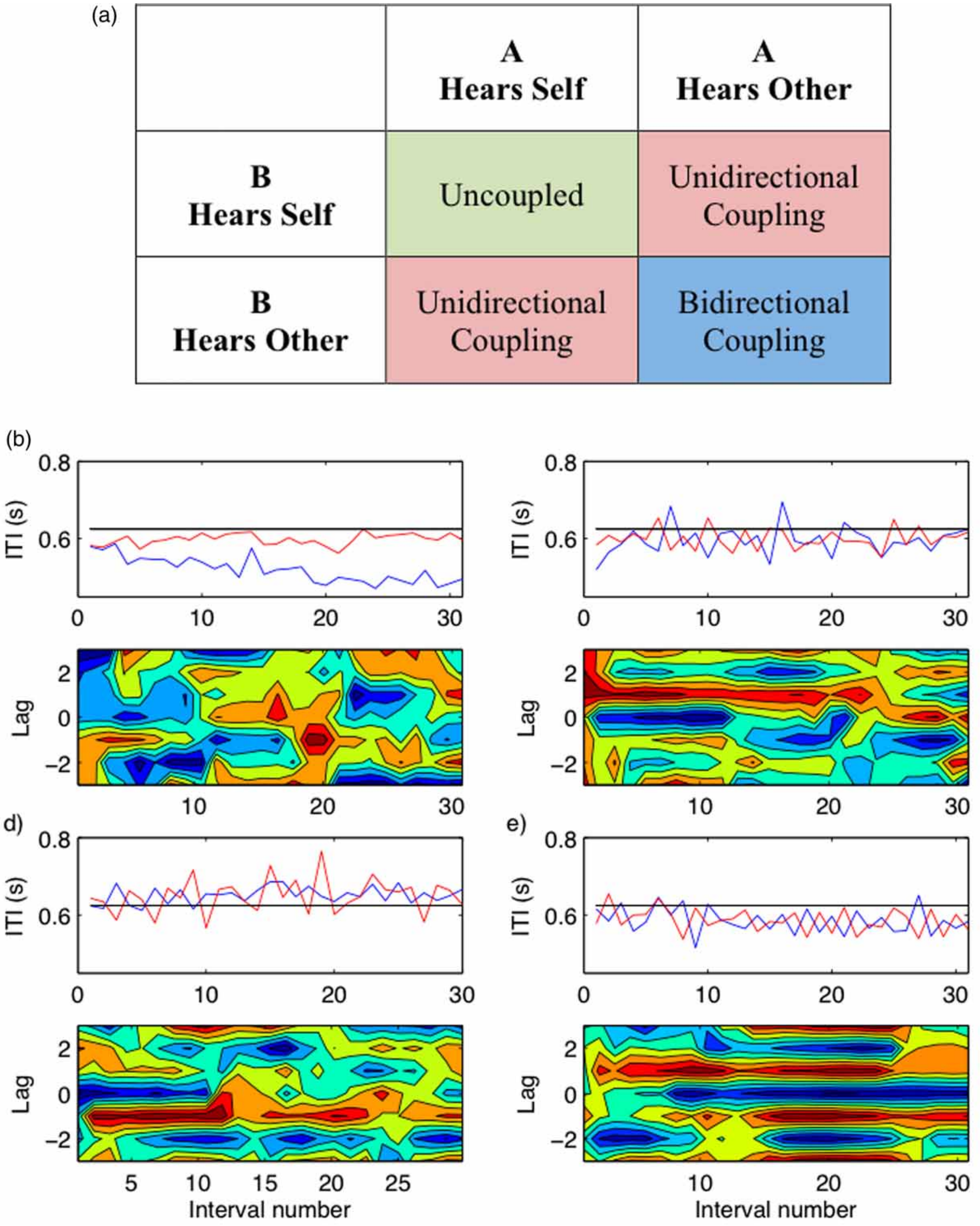
The positive correlations at lag 1 reflect the tendency of each member to adapt towards the previous ITI of the other member, by producing a shorter ITI when the other's last had been shorter and longer if the other's had been longer. Both members do this simultaneously, and this mutual adaptation leads to negative correlations at lag 0, since when one member has sped up, the other has slowed down. The means and standard errors of lag 0 coefficients for the first six ITI windows (i.e., 1-6, 2-7, etc.) corresponding to the bidirectional coupling condition are summarized in Figure 3. As can be seen from the figure, the lag 0 correlation coefficients are negative on the very first six intervals already, showing that mutual adaptation takes place from the very beginning of the tapping trial.

Synchronization indices of tapping pairs

The synchronization regime was found across all conditions, but to different degrees. The indices were found to be significantly different for 96, $F(2, 39) = 5.33$, $p = .009$, and 120, $F(2, 42) = 4.94$, $p = .0119$, bpm. Tukey's HSD (honestly significant difference) tests revealed lower synchronization indices for the unidirectional coupling scenario than for the bidirectional condition when both were hearing each other. No significant differences were found in synchronization when tapping along with the computer versus the bidirectional coupling condition. The means and standard errors of the indices are summarized in Table 2.

Accuracy in keeping the given beat

In order to evaluate how accurate participants were at keeping the given beat, we computed a 2 × 2 ANOVA (Figure 1a), comparing the means of the absolute ITI difference from the target metronome for the different coupling conditions. We



	A Hears Self	**A Hears Other**
B Hears Self	Uncoupled	Unidirectional Coupling
B Hears Other	Unidirectional Coupling	Bidirectional Coupling

Figure 1. *Windowed cross-correlations of one dyad's ITIs (intertap intervals) for the (a) 2 × 2 design with Member 1's and Member 2's auditory feedback as the factors. Top plots: ITIs of Participant 1 (red) and Participant 2 (blue) against the interval number. Bottom plots: windowed cross-correlations with a lag range from −3 to 3 plotted against interval number. The colour-map correlation coefficient values range from −.8 (dark blue) to +.8 (dark red); (b) uncoupled condition—both hearing the self; (c) and (d) unidirectional coupling condition—both hearing Member 2 and Member 1, respectively; (e) bidirectional coupling condition—hearing each other.*

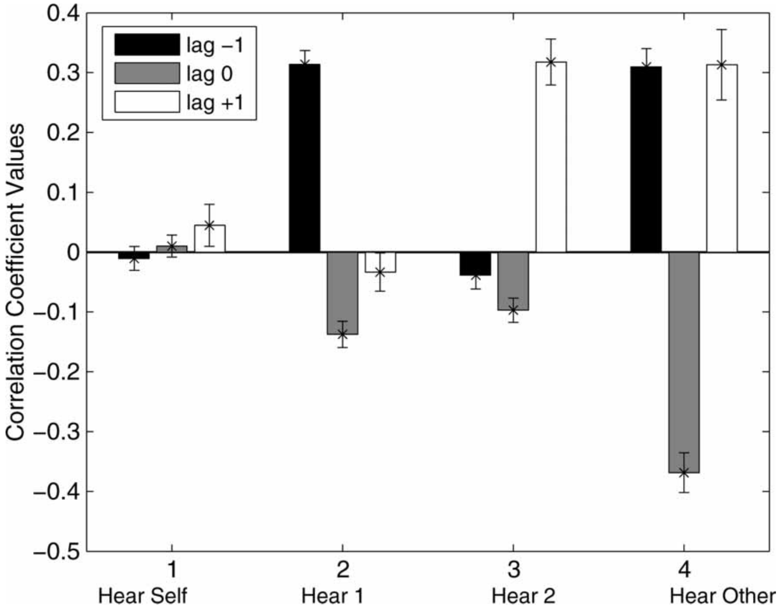


Figure 2. *Windowed cross-correlation lag −1, 0, and +1 means and standard errors for the 2 × 2 design for a tempo of 96 bpm (beats per minute). Conditions: (1) uncoupled condition—hearing the self; (2) and (3), unidirectional coupling—both hearing Member 1 and Member 2, respectively; and (4) bidirectional coupling–hearing each other.*

found a significant effect of both factors—namely, what the other member was hearing, $F(1, 27) = 17.80$, $p < .001$ for 96 bpm, and $F(1, 29) = 5.36$, $p = .028$ for 120 bpm; and the self auditory feedback, $F(1, 27) = 13.22$, $p = .001$ for 96 bpm, and $F(1, 29) = 16.08$, $p < .001$ for 120 bpm; as well as the interaction, $F(1, 27) = 18.79$, $p < .001$ for 96 bpm, and $F(1, 29) = 4.93$, $p = .034$ for 120 bpm. Participants were significantly worse at keeping the given tempo when listening to the other member and even worse in the bidirectional coupling condition. For the

Table 1. *Summary of significance values from the 2 × 2 MANOVA design with Member 1's and Member 2's auditory feedback as the factors*

		Lag -1		*Lag 0*		*Lag +1*	
Tempo	*Effect of feedback*	*F-ratio*	*p*	*F-ratio*	*p*	*F-ratio*	*p*
96 bpm	Member 1: other vs. self		*ns*	35.24	.0001	39.081	.0001
	Member 2: other vs. self	120.824	.0001	95.044	.0001		*ns*
	Interaction		*ns*	9.825	.008		*ns*
120 bpm	Member 1: other vs. self		*ns*	103.606	.0001	41.169	.0001
	Member 2: other vs. self	58.423	.0001	24.807	.0001		*ns*
	Interaction		*ns*		*ns*		*ns*
150 bpm	Member 1: other vs. self		*ns*	60.873	.0001	62.145	.0001
	Member 2: other vs. self	88.024	.0001	86.931	.0001		*ns*
	Interaction		*ns*	8.542	.011		*ns*

Note: Auditory feedback: each hearing self or other. MANOVA = multivariate analysis of variance. bpm = beats per minute.

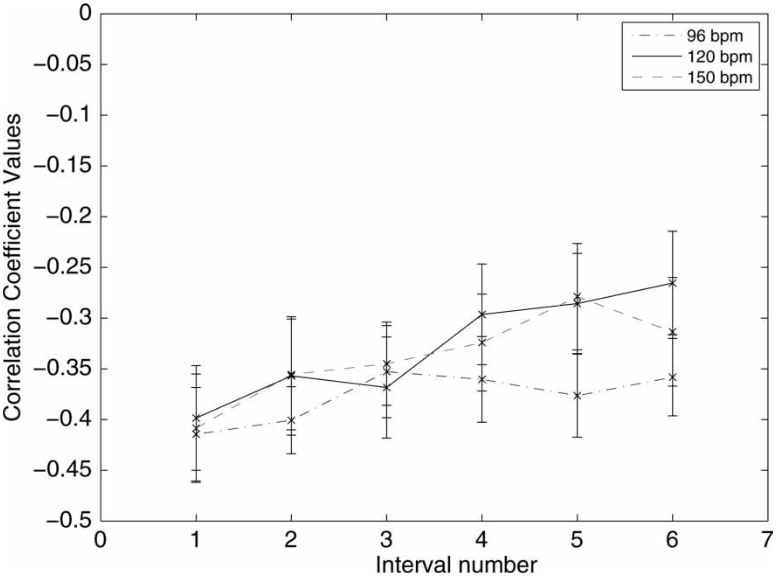


Figure 3. *Means and standard errors of lag 0 windowed cross-correlation coefficient values for the first six ITI windowed 'shifts' in the bidirectional coupling condition.*

150 bpm tempo, the difference from the target metronome was also greater when the participant could hear the other, $F(1, 29) = 14.26, p = .001$, but this was not affected by what the other member was hearing.

Discussion

Much of the research on interpersonal synchronization has considered this phenomenon either in terms of dynamical properties of self-organization (Haken et al., 1985; Schmidt & Richardson, 2008) or from the perspective of social psychology as a marker of social connectedness (Bernieri, 1988; Chartland & Bargh, 1999). In this study, we identified a stable pattern of interpersonal coordination, which has never before been reported. We found that when dyads were mutually coupled to one another, they corrected the duration of their ITIs in opposite directions on a tap-to-tap basis in a mutual attempt to synchronize with one another. These findings are novel as they show that, in a jointly coordinated tapping task, there is no evidence for the emergence of a leader–follower strategy, but rather a continuous mutual adaptation on a short, millisecond timescale.

Joint action tasks are usually thought of as consisting of many complex processes leading to a final

Table 2. *Means and standard errors of synchronization indices for each tempo, for hearing the computer, bidirectional, and unidirectional coupling conditions*

	96 bpm		*120 bpm*		*150 bpm*	
Condition	*Mean SI*	*SE*	*Mean SI*	*SE*	*Mean SI*	*SE*
Hearing computer	.9593	.0043	.96	.0034	.9099	.019
Bidirectional	.96	.007	.9565	.0055	.9325	.0168
Unidirectional	.9318	.0088	.9213	.0154	.8956	.0287

Note: SI = synchronization index. bpm = beats per minute.

outcome. How people coordinate their goals and actions to achieve these tasks together has been investigated in various experiments on greater time scales, looking at overall task performance of dyads versus individual performance (Knoblich & Jordan, 2003; Reed et al., 2006; Sebanz, Knoblich, & Prinz, 2005). However, in this experiment we were particularly interested in the mechanism enabling coordination, so our first aim was to focus on what happens in real time on a response-to-response level by treating the two time series corresponding to the ITIs of each member of a pair as only having local stationarities, hence computing windowed cross-correlations.

The windowed cross-correlations revealed that dyads were unable to achieve a positive lag 0 correlation. Instead, they adopted oscillatory behaviour, whereby in unidirectional coupling, the "follower's" ITIs would oscillate around those of the member that was being heard, as they adjusted the timing of their next tap based on the previous ITI of the other member. Similarly, in a two-way interaction, both members adopted this behaviour, thereby resulting in a mutual continuous adaptation to the other's output. This is reflected by the continuously positive lag −1 and +1 correlation coefficients and a negative lag 0 coefficient. This behaviour was seen on each tap instance and was maintained throughout the trial across all 15 pairs. The negative lag 0 coefficients were already found for the very first six tapping intervals (Figure 3), showing that this adaptation begins to take place immediately at the beginning of the trial. The dyads thus became a coupled unit, consisting of two followers mutually adapting to one another on a millisecond timescale. These results show that coordination can be a result of a highly adaptive process that takes place almost instantaneously as people attempt to align within milliseconds by mutually following the previous tap of the other. Each member speeds up when the other has been faster on the last tap and slows down if the other has been slower. Thus they both become followers of the other's prior tap and hence "hyper-followers". Given that this happens mutually and simultaneously, their ITIs end up oscillating in opposite directions, as reflected by the interaction at lag 0 for two of three tempi.

Analysis of task performance revealed that participants were just as good at synchronizing with the other person in the bidirectional coupling condition as they were with the computer. However, they were worse at synchronizing when forced into a leader−follower scenario (i.e., unidirectional coupling) for the 96 and 120 bpm tempi. The computer metronome was a precise beat-keeper, inherently more predictive than the other person. We thus expected that people would synchronize better with a predictable partner than an unpredictable one, irrespective of whether that partner was responsive. However, while the ability to predict the subsequent tapping instance seems to be important, as shown by the poorer synchronization in the unidirectionally coupled case than with the computer, it does not seem to be as crucial when the less predictable partner is responsive (i.e., in the bidirectionally coupled case) and consequently adaptive as shown by the cross-correlations.

These findings show that it is possible to achieve equally good synchronization with a partner that is unpredictable but responsive, compared to a partner (i.e., computer) that is predictable but nonresponsive. However, the task to synchronize is significantly more difficult with a partner that is both unpredictable and nonresponsive. This suggests that successful coordination is based not only on the prediction accuracy of the partner's future actions and is hence anticipatory (Knoblich & Jordan, 2003), but also (and perhaps more importantly) on the mutual adaptability to the current action. We therefore propose that successful interpersonal coordination depends on the abilities to (a) predict the other's subsequent action, and (b) adapt promptly. While these anticipatory and adaptive skills arise on an intrapersonal level, they rely strongly on the ongoing interpersonal interaction, as shown by the superior synchronization in the bidirectional coupling condition compared to the one with an unresponsive coparticipant. The cross-correlation markers of this behaviour are encapsulated by the interaction at lag 0, showing that the oscillatory, mutually predictive, and adaptive behaviour in the bidirectional coupling condition cannot be fully predicted from how each individual follows the other one, but rather emerges from the joint, mutual interaction. The two individual systems become coupled with each other as a result of the interaction, out of which an interactive unit of two "hyper-followers" emerges. Moreover, this unit affords a mutual adaptation among pairs rather than a process that is more driven by one of the partners.

It remains to be investigated whether tapping along with a computerized model that is both predictive and adaptive would produce the same behaviour. Furthermore, we are interested to see how competence would feed into these couplings and whether with sufficient practice people (i.e., professional musicians) become followers of a virtual beat and therefore more predictive.

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