

The role of reciprocity in dynamic interpersonal coordination of physiological rhythms

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ABSTRACT

A central question in social cognition research is how people coordinate their bodily rhythms, and how important reciprocity of interaction is for interpersonal coordination. Previous research has primarily focused on interpersonal action coordination, which has been shown to be facilitated by mechanisms of prediction and mutual adaptation. Recent research is beginning to show that people also coordinate their physiological rhythms (i.e., respiration, heart rhythms) when they engage in natural forms of social interaction, such as conversation, choir singing, and rituals. However, the mechanisms underlying interpersonal physiological synchronization remain obscure, and could provide insight into the dynamic mechanisms that underlie continuous and regulatory, rather than instrumental, joint actions. Using real-time biofeedback, we investigated whether people synchronize their respiration rhythms by forming a joint dynamical system through reciprocity of interaction, or by producing more predictable respiration rhythms. Our results show that people are more in-phase synchronized but less phase-locked when interacting bidirectionally versus unidirectionally (online), but there is no difference in synchronization during reciprocal interaction and when adapting unidirectionally (offline) to recordings of respiration signals that emerged during the reciprocal interaction. Moreover, the strength of synchronization is driven by the predictability of the respiration rhythms that emerge in the bidirectional interaction – specifically, the slowing of breathing rhythms and stability of breathing frequencies – rather than the online mutual adaptation itself. These results suggest that coordination is facilitated by the emergence of predictable breathing patterns, rather than reciprocity itself.

1. Introduction

A key mechanism underlying social interaction is the ability to mutually coordinate and align actions, emotions, and mental states with others (Sebanz & Knoblich, 2021). People coordinate with one another in order to achieve joint goals, often spontaneously and without much conscious effort, such as when coordinating breakfast with their partner, assembling furniture together, or playing a musical duet. Given that coordination relies on an interaction between at least two people, the field of social cognition has moved towards studies of two- or more persons engaged in interaction with each other in order to uncover the underlying interpersonal dynamical processes (De Jaegher, Di Paolo, & Gallagher, 2010; Dumas, 2011; Konvalinka & Roepstorff, 2012; Schilbach et al., 2013). Within this framework, a central question has been what mechanisms underlie interpersonal coordination, and more

specifically, to what extent is coordination facilitated by reciprocity of interaction versus asymmetric adaptation, e.g., as seen across leader-follower dynamics.

Interpersonal coordination has been widely studied between people's movements, resulting from the tight coupling of periodic behaviour (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt & O'Brien, 1997; Skewes, Skewes, Michael, & Konvalinka, 2015). For example, it has been shown that people synchronize their strides when they walk next to each other (van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008), their postural sways when they converse together (Shockley, Santana, & Fowler, 2003), and their eye movements when engaged in a dialog (Richardson, Dale, & Kirkham, 2007). Interpersonal synchronization can be both intentional and spontaneous (Koban, Ramamoorthy, & Konvalinka, 2019; Richardson, Marsh, et al., 2007), and has been proposed to have a functional role in social bonding

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(Marsh, Richardson, & Schmidt, 2009), by increasing subsequent cooperation (Wiltermuth & Heath, 2009) and affiliation (Hove & Risen, 2009). Recent research has shown that people also synchronize their cardiac and respiratory rhythms with each other (see Palumbo et al., 2016 for a review) when they engage in natural forms of interaction, such as high-arousal rituals (Konvalinka et al., 2011), natural conversation (McFarland, 2001), choir singing (Müller & Lindenberger, 2011), or when coordinating behaviour (Fusaroli, Bjørndahl, Roepstorff, & Tylén, 2016; Noy, Levit-Binun, & Golland, 2015). This phenomenon has also been reported between romantic couples (Goldstein, Weissman-Fogel, & Shamay-Tsoory, 2017; Helm, Sbarra, & Ferrer, 2012; Prochazkova, Sjak-Shie, Behrens, Lindh, & Kret, 2021) and mother-infant dyads (Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011; McFarland, Fortin, & Polka, 2020), and hence may also have a role in the formation of social bonds (for recent reviews, see e.g., Cross, Turgeon, & Atherton, 2019; Michael, McEllin, & Felber, 2020).

However, the underlying mechanisms that give rise to interpersonal physiological synchronization are not known, and could be relevant for understanding the general mechanisms of dynamic joint actions. Within joint action research of discrete or intermittent action coordination (e.g., finger tapping), studies have shown that key mechanisms that facilitate interpersonal coordination are prediction of others' subsequent actions (Gebauer et al., 2016; Keller, Novembre, & Hove, 2014; Pecenka & Keller, 2011; Sebanz & Knoblich, 2009; Vesper, van der Wel, Knoblich, & Sebanz, 2013), mutual adaptation in symmetric tasks (Goebel & Palmer, 2009; Konvalinka, Vuust, Roepstorff, & Frith, 2010; Loehr & Palmer, 2011), and asymmetric adaptation (e.g., where one adapts more than the other, or along different dimensions) in asymmetric tasks (Curioni, Vesper, Knoblich, & Sebanz, 2019; Richardson et al., 2015; Skewes et al., 2015; Vesper et al., 2013). Similarly, studies of interpersonal coordination of continuous and dynamic movements have shown that synchronization is particularly facilitated by mutual reactive-predictive processes, indicative of spontaneous and implicit agreement on future behaviour (e.g., motion) between interacting partners (Noy, Dekel, & Alon, 2011). In the study by Noy and colleagues, pairs of expert improvisors were asked to improvise and synchronize motion together in a joint condition, or with a designated leader and follower. While a mathematical model suggested that the improvisors produced more synchronized movements in the joint condition, due to the mutual, and hence reciprocal, feedback (Noy et al., 2011), the participants also converged on a universal stroke of motion in this condition – while producing different individual strokes as leaders (Hart, Noy, Feniger-Schaal, Mayo, & Alon, 2014). These studies raise the question of whether it is the mutual adaptation itself that maximizes coordination, or predictable patterns of individual behaviour which emerge during reciprocal interactions.

But how do we disentangle adaptation and prediction, and reciprocal versus non-reciprocal interactions? Reciprocal interactions are, by definition, symmetric in terms of participants' mutual contributions, as they involve a mutual exchange of information, with two co-actors equally contributing to the outcome. In contrast, non-reciprocal interactions are asymmetric, with one person contributing more to the interaction outcome than the other. For example, in the case of a leader-follower interaction, the follower makes an effort to adjust to the leader, while the leader focuses more on self-generated actions (Curioni et al., 2019; Fairhurst, Janata, & Keller, 2014; Richardson et al., 2015; Skewes et al., 2015). Despite the importance reciprocity has been ascribed in social cognition research (Dumas & Fairhurst, 2021), very few studies have directly addressed the role of reciprocity on joint action outcomes (Mahmoodi, Bahrami, & Mehring, 2018; Noy et al., 2011; Skewes et al., 2015), particularly within interpersonal coordination. The key question that remains is, is it reciprocity that drives coordinative success in mutually coupled tasks, or do people produce more predictable patterns when mutually coupled to each other?

Here, in order to investigate the role of reciprocity in interpersonal coordination of physiological rhythms, we varied reciprocity by

manipulating the directionality of coupling to investigate how people achieve coordination in real-time. To achieve this, we asked pairs of participants to synchronize their respiration rhythms, and we manipulated the availability of real-time visual biofeedback the participants received about one another. In Experiment 1, we looked at the effect of bidirectional (i.e., mutual) versus unidirectional feedback on coordination. Participants received real-time visual feedback of each other's breathing signals in the bidirectional condition, and real-time visual feedback of a third person's breathing signals in the unidirectional condition (with the confederate receiving no feedback, see Fig. 1). Rather than implementing a unidirectional condition in pairs (with one participant at a time receiving feedback about the other), we added a third person (confederate), in order to avoid participants being aware of the feedback manipulation and learning from each other's breathing patterns. In Experiment 2, we addressed whether interpersonal coordination was facilitated by the reciprocity (online interaction) or emergence of predictable breathing patterns in the bidirectional condition, by having a new set of participants coordinate their breathing to a replay of respiration rhythms from the bidirectional condition (offline control interaction). The crucial difference between the offline control interaction in Experiment 2 and the unidirectional condition in Experiment 1 is that even though they are both unidirectional interactions (with only one partner receiving feedback of the other), the producers of the breathing patterns in Experiment 2 were interacting with and adapting to another person when producing the breathing patterns, while the confederate of Experiment 1 was not adapting to anyone. The contrast between *online* and *offline control* interaction is thus between interpersonal coordination being facilitated by reciprocity (between bidirectionally coupled partners) and interpersonal coordination being facilitated by production of predictable breathing patterns (by producers of breathing, while adapting to another person), respectively. Therefore, if interpersonal coordination is facilitated by reciprocity, we would predict better synchronization in bidirectional versus unidirectional tasks, as well as in online (bidirectional) versus offline interactions. Alternatively, if interpersonal coordination is facilitated by production of more predictable patterns when mutually interacting, we would predict better synchronization in bidirectional versus unidirectional tasks, but no differences between online versus offline interactions. Finally, we address whether inducing interpersonal physiological synchronization has a role in social bonding.

2. Materials and methods

2.1. Participants

Twenty-six participants participated in pairs in Experiment 1 (9 mixed gender, 4 female pairs). The sample size was based on similar studies of interpersonal synchronization at the time when the experiment was designed (e.g., Dumas, Nadel, Soussignan, Martinerie, & Garnero, 2010; Fusaroli et al., 2016; Noy et al., 2015; Vesper et al., 2013). Additionally, we ran a post-hoc power analysis to ensure that we had sufficient power. Based on the effect sizes from Experiment 1, to achieve 80% power, a sample size of 5, 23, and 26 would be necessary, corresponding to the distribution of the data for the main analyses (mean relative phase, in-phase % occurrence, and phase locking values, respectively). Given that one pair was discarded because the participants knew each other, our sample size of 24 participants (interacting with each other or another person) is sufficient to achieve 80% power for synchronization analyses, and only slightly underpowered for in-phase % occurrence.

Twenty-four gender-matched participants to those in Experiment 1 participated in Experiment 2. They all gave written, informed consent. Ethics approval was obtained from the United Ethical Review Committee for Research in Psychology, Hungary (EPKEB), and was in agreement with the Declaration of Helsinki.

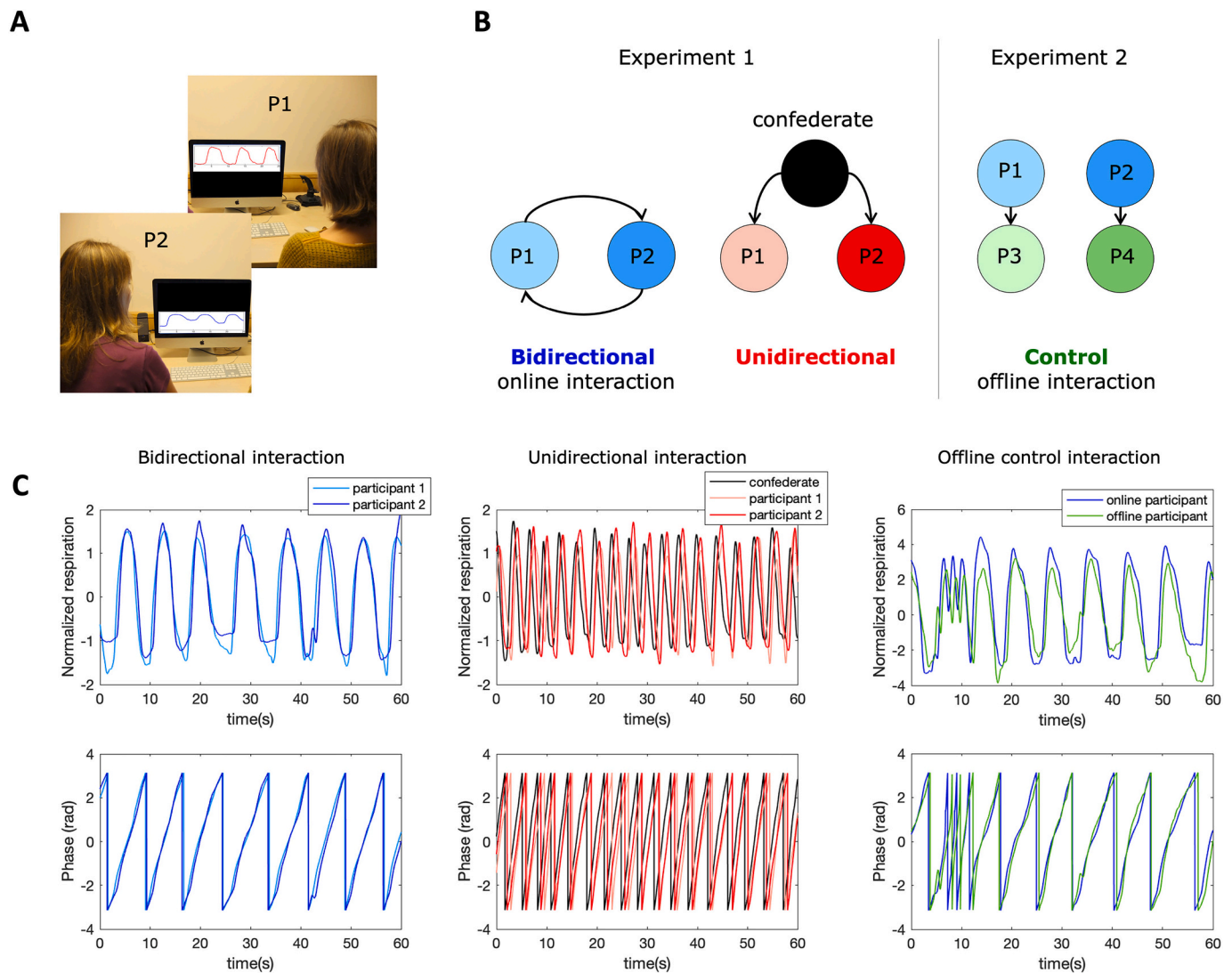


Fig. 1. **A.** Experimental setup: Pairs of participants received visual real-time biofeedback of another person's breathing rhythm; **B.** Experimental task: in Experiment 1, participants engaged in bidirectional (online) interaction and in unidirectional interaction with a third person; in Experiment 2, the respiration data produced by participants from the bidirectional condition in Experiment 1 was fed back to a new set of participants in an offline control interaction; **C.** Normalized respiration (top) and phase (bottom) data from sample pairs during 1 min of the bidirectional (left), unidirectional (middle), and offline control (right) interactions.

2.2. Task and procedure

In Experiment 1, participants from each pair were seated in two separate rooms, and did not see each other prior to the experiment. They were told they would engage in a synchronization task with two different people, seated in different rooms, and given real-time feedback of each person's breathing across two interactions, while their respiration and ECG (only respiration data are reported in this paper) were recorded. Prior to and post each interaction task, we recorded a 5-min resting baseline. In the bidirectional condition, participants were given real-time mutual biofeedback of each other's respiration rhythms (Fig. 1B, bidirectional online interaction), but not their own. In the unidirectional condition, they were given real-time unidirectional biofeedback of a confederate's respiration, with the confederate receiving no feedback (Fig. 1B unidirectional interaction). The confederate was instructed to breathe at rest. While they were aware of the experimental manipulations, they were not told when their respiration would be displayed on the participants' screens. Each interaction condition lasted 5 min. They were asked to synchronize their own breathing to the breathing visualized on the screen. The order of interaction conditions was counterbalanced across pairs. Participants were not aware of

the manipulation, i.e., whether the other participant had feedback or not. After each interaction, prior to a baseline recording, they filled in a questionnaire, rating on a 7-point Likert scale: task difficulty, enjoyment, how synchronized they felt with the other, how likable the partner was, as well as the inclusion of other in the self (IOS). This was used to test whether reciprocity of interaction in the physiological domain had an effect on social bonding, by computing paired *t*-tests between the bidirectional and unidirectional interactions, and independent *t*-tests between bidirectional and control conditions. In addition, we computed correlations between how well participants synchronized (in terms of mean relative phase, in-phase % occurrence, and PLVs, see below for descriptions of these measures) and the social bonding measures (liking and IOS).

In Experiment 2, participants were recruited individually, and given recorded biofeedback of participants' breathing signals from the bidirectional condition in Experiment 1 (Fig. 1B, offline control condition). They were instructed to synchronize their own breathing to the breathing visualized on the screen, which they were told corresponded to real-time feedback of another person's breathing, seated in a different room (hence keeping consistent instructions between Experiment 1 and 2). The synchronization task lasted 5 min. Their baselines were recorded

prior to and after the interaction condition, and they filled in the same questionnaire as in Experiment 1, after the offline control condition.

In Experiment 1, the signals were presented in real-time via the Acknowledge interface (Fig. 1A). In Experiment 2, the pre-recorded signals were resampled to the frame rate of the monitor (60 Hz), played back via Psychtoolbox, and synchronized to the physiological recordings by sending triggers using the STP100C-C module.

2.3. Physiological recordings and phase analysis

Respiration data were recorded using the BIOPAC wireless MP150 Bionomadix system, with a sampling rate of 1000 Hz. The data were downsampled to 100 Hz, detrended, and normalized by computing z-scores. All analyses were computed in MATLAB.

Phase was estimated by applying the Hilbert transform. The respiration for each participant l (1 or 2) in pair k was transformed to a complex signal, $R_{kl}(t_m)$, where $m = 1, 2, \dots, T$ time samples, with a real and imaginary part, $r_{kl}(t_m)$ and $u_{kl}(t_m)$, respectively. Instantaneous phase, $\varphi_{kl}(t_m)$, was calculated as:

$$\varphi_{kl}(t_m) = \text{atan} \frac{u_{kl}(t_m)}{r_{kl}(t_m)} \quad (1)$$

A sample pair's normalized respiration (z-scores) and phase data are shown in Fig. 1C for 1 min of the bidirectional and unidirectional interactions, as well as for a sample pair for the offline control interaction.

Relative phase was computed by subtracting participant one's continuous phase signal from participant two's in the bidirectional interaction; and by subtracting each participant's phase signal from the confederate's in the unidirectional interaction. In Experiment 2 (offline control condition), each participant's phase signal was subtracted from the corresponding participants' phase in the bidirectional condition of Experiment 1. Relative phase data were then transferred to range from -180 to $+180$ degrees, and % occurrence was calculated in 2 degree bins (Richardson, Marsh, et al., 2007). A lack of synchronization resembles a uniform distribution across all the relative phase bins, in-phase synchronization has a peak around 0 degrees, anti-phase around -180 or $+180$ degrees, and a constant phase lag between the signals has a peak between 0 and 180 degrees (or -180 and 0).

In order to statistically compare the bidirectional (12 pairs) and unidirectional (24 pairs) interactions, we assigned the first half of the bidirectional interaction to participant 1, and the second half to participant 2, with the relative phase, RP , defined as:

$$RP_{12}(t_m) = \varphi_1(t_m) - \varphi_2(t_m) \quad (2)$$

when $t_m = 1, 2, \dots, 15,000$ time samples, corresponding to the first half of the interaction (2.5 min), and

$$RP_{21}(t_m) = \varphi_2(t_m) - \varphi_1(t_m) \quad (3)$$

when $t_m = 15,001, \dots, 30,000$ time samples, corresponding to the second half of the interaction. This relationship and corresponding time samples of interaction were kept consistent for the unidirectional and offline control (Experiment 2) interactions. Notably, there was no significant difference in synchronization between the first half and the second half of the interaction in the bidirectional condition, across mean relative phase, absolute mean relative phase, in-phase occurrence, or phase locking values (all $ps > 0.1$, tested using paired t -tests).

To calculate phase locking of interpersonal breathing rhythms, phase locking values (PLVs) were computed for all interaction conditions, e.g., for the bidirectional condition, each pair k , and T number of time samples:

$$PLV_k = \frac{1}{T} \left| \sum_{t=1}^T e^{i[\varphi_{k1}(t) - \varphi_{k2}(t)]} \right| \quad (4)$$

Mean relative phase and phase locking values were compared in the

bidirectional and unidirectional conditions in Experiment 1, and the online bidirectional versus offline control conditions in Experiment 2, using Welch's t -tests, given normally distributed data with unequal variances. Normality was checked using Shapiro-Wilk tests. In-phase occurrence (defined as % occurrence in the $-10:10$ degree window) was not normally distributed, and hence compared using Mann-Whitney U tests.

2.4. Predictability of breathing patterns

In order to calculate the predictability of breathing patterns across the conditions, we focused on two measures: the mean respiration period and the variability of the dominant respiration frequency. These two measures were chosen as they represent the real-time predictability of a signal (i.e., the slower one breathes, the easier it is to predict the signal in real-time and react to changes) and the predictability of the breathing rate (the lower the variability, the more predictable), respectively.

The **mean respiration period** was calculated for each participant and interaction using a peak-detection algorithm, with the periods between the peaks averaged for each interaction. Each data set was manually checked, and any missed peaks were inserted. Since the data were not normally distributed, we compared the mean respiration periods using the Wilcoxon signed-rank test in Experiment 1, and Mann-Whitney U test in Experiment 2. To test the hypothesis that interpersonal coordination was facilitated by slowing down the breathing (and hence, real-time predictability of the signal), we fit a linear regression model with mean respiration periods in the bidirectional condition as a predictor variable, and in-phase synchronization (% occurrence of relative phase in the $-10:10$ degree window) and phase locking values as response variables. Here the first half of the trial was assigned to participant one, and the second half to participant two, as with the phase analysis. To test whether interpersonal coordination was facilitated by emergence of predictable patterns by slowing down the breathing, we fit a linear regression model between the mean respiration periods produced by participants in the bidirectional condition and in-phase synchronization/phase locking values in the offline control interaction in Experiment 2, using whole trials.

The **variability of the dominant respiration frequency** was measured by first computing the continuous (Morse) wavelet transform of the respiration signal over time (for each participant/interaction). A dominant frequency of respiration (max power) was then computed across each 10 s window (30 windows for a 5-min interaction). Finally, the variability of the dominant respiration frequency was calculated as the coefficient of variation (CoV) of the dominant respiration frequencies across the 10 s windows of each interaction. To test the hypothesis that interpersonal synchronization (i.e., phase locking) was facilitated by the stability (and hence lower variability) of the respiration frequency, we fit a linear regression model between the variability of the dominant respiration frequency in the bidirectional condition and the phase locking values (half-trial assignment); and the variability of the dominant respiration frequency of the participants in the bidirectional condition and the phase locking values in the offline control interaction in Experiment 2 (whole trials).

Finally, in order to check whether being aware that other participants would be seeing and synchronizing to one's respiration signal would have an effect on the confederate's breathing pattern, we ran a post-hoc analysis, contrasting their mean respiration period and variability of the dominant respiration frequency during the unidirectional interaction versus the preceding 5-min baseline. This was done using paired t -tests, with the assumption that interactions with different individuals were independent from each other.

3. Results

Results from Experiments 1 and 2 are reported together in the

following sections.

3.1. Questionnaire results

There were no significant differences in reported task difficulty, enjoyment of the task, liking of the other participant, or inclusion of the other in the self between the bidirectional and unidirectional interactions (all p 's > 0.1). However, the participants felt more synchronized with the other person in the unidirectional ($M = 5.00$, $SD = 0.93$) interaction compared to the bidirectional ($M = 4.04$, $SD = 1.73$) one ($t(23) = -2.1375$, $p = 0.0434$, $\eta^2 = 0.1657$). There were no reported differences between the bidirectional and offline control condition (all p 's > 0.05). In addition, we found no significant correlations between how well participants synchronized (in terms of mean relative phase, in-phase % occurrence, and PLVs) and the social bonding measures (liking and inclusion of the other in the self), all p 's > 0.1.

3.2. Relative phase distribution and phase locking values

The distribution of relative phase was calculated between participant 1 and 2's phase signals in the bidirectional condition, between each participant and the confederate's phase in the unidirectional condition, and between the phase signals of the participants from the bidirectional condition (Experiment 1) and corresponding participants from Experiment 2 in the offline control condition (Fig. 2A). There was a significant difference in mean relative phase (in degrees) between the bidirectional ($M = -0.9924$, $SD = 34.63$) and unidirectional ($M = 57.53$, $SD = 19.95$) interaction conditions, $t(36.75) = -7.17$, $p < 0.001$, $\eta^2 = 0.5281$, but no

significant difference between bidirectional (online) and offline control ($M = 15.36$, $SD = 20.57$) conditions, $p = 0.054$ (Fig. 2B, left panel).

Participants were more in-phase during the bidirectional ($M = 12.49$, $SD = 11.30$) interaction than the unidirectional ($M = 5.42$, $SD = 5.35$) interaction, as calculated using in-phase % occurrence, $U = 179$, $p = 0.0253$, $\eta^2 = 0.2176$. There was no difference in in-phase occurrence between the bidirectional online interaction and the offline control ($M = 11.09$, $SD = 9.39$) interaction, $p = 0.7337$ (Fig. 2B, middle panel).

Participants were less phase locked in the bidirectional ($M = 0.5619$, $SD = 0.2887$) than the unidirectional ($M = 0.7292$, $SD = 0.0814$) interaction, as calculated using phase locking values, $t(26.631) = -2.733$, $p = 0.011$, $\eta^2 = 0.1397$. There was no difference in phase locking values between the bidirectional online interaction and offline control interaction ($M = 0.4437$, $SD = 0.2410$), $p = 0.1308$ (Fig. 2B, right panel).

3.3. Slower breathing facilitates in-phase synchronization

There was no significant difference in the mean respiration period between the bidirectional ($M = 4.63$, $SD = 3.36$) and unidirectional ($M = 3.46$, $SD = 0.28$) interactions ($p = 0.2087$), or the bidirectional and offline control ($M = 4.64$, $SD = 2.79$) interactions ($p = 0.6725$). However, the mean respiration periods were qualitatively more widely distributed in the bidirectional and control interactions than the unidirectional interaction (Fig. 3A). Hence, we tested whether there was an association between the mean respiration period and how well participants synchronized with each other. As can be seen in Fig. 3B, the slower the participants were breathing during the bidirectional interaction, the

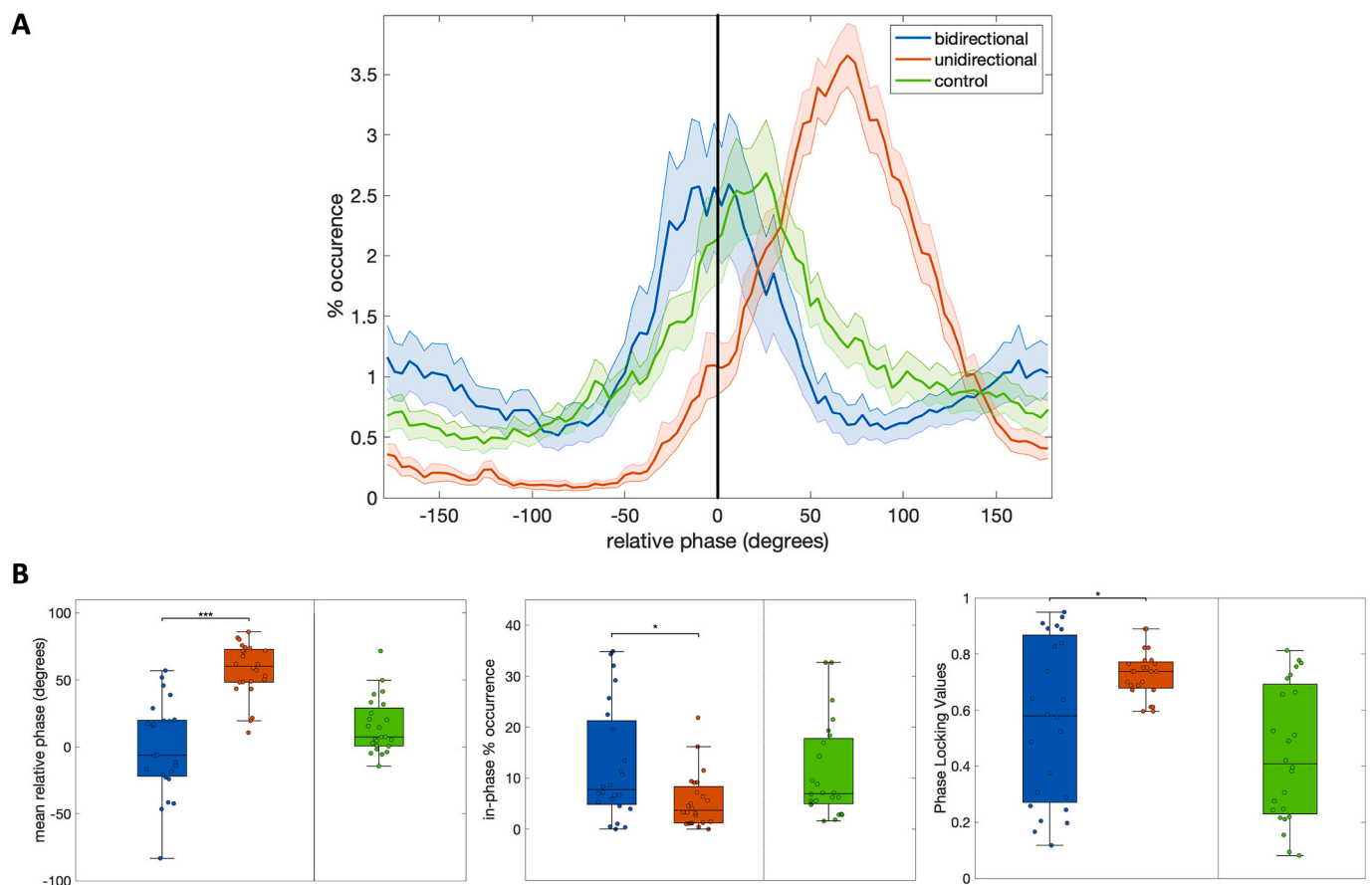


Fig. 2. A. Distribution of relative phase (from -180 to 180 degrees) across the three interaction conditions; B. Box plots for the bidirectional (blue) and unidirectional (red) interactions from Experiment 1, and offline control (green) interaction from Experiment 2. Left panel: mean relative phase in degrees, middle panel: in-phase % occurrence, right panel: phase locking values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

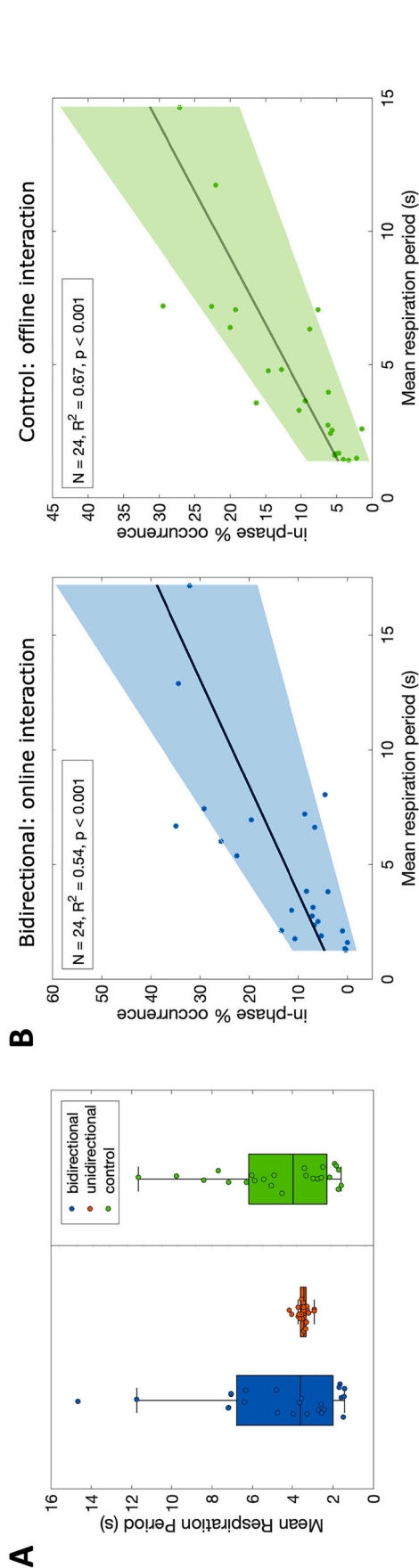


Fig. 3. A. Box plots of the mean respiration period (seconds) across the whole interaction. B. Left panel: linear regression model showing a positive association between the mean respiration period (across 24 participants, where the first half of interaction is attributed to participant 1 and the second half to participant 2) and in-phase % occurrence in the bidirectional online interaction, $r^2 = 0.538, p < 0.001$; Right panel: a positive association between the mean respiration period (across the whole interaction) in the bidirectional condition and in-phase % occurrence during the offline control interaction, $r^2 = 0.669, p < 0.001$. Shaded areas represent 95% confidence intervals.

more in-phase synchronized they were ($r^2 = 0.538, p < 0.001$), and the better participants in Experiment 2 could synchronize to them unidirectionally ($r^2 = 0.669, p < 0.001$). The slower breathing participants were also more phase-locked in the bidirectional interaction ($r^2 = 0.466, p < 0.001$), and the slower they were, the more phase-locked participants in the offline control condition were to their signal ($r^2 = 0.414, p < 0.001$).

There was no significant difference in the confederate's mean respiration period between the unidirectional interaction ($M = 3.49, SD = 0.32$) and the preceding baseline ($M = 3.40, SD = 0.26$), $p = 0.3823$.

3.4. Stability of the dominant respiration frequency facilitates phase-locking

The variability of the dominant respiration frequency was significantly higher (and hence less stable) in the bidirectional ($M = 0.47, SD = 0.41$) compared to the unidirectional ($M = 0.15, SD = 0.15$) interaction ($Z = 4.286, p < 0.001$, effect size $r = 0.8748$), while there was no difference between the bidirectional and control ($M = 0.42, SD = 0.30$) conditions ($p = 0.99$), as shown in Fig. 4C. Differences between two sample participants (from two different pairs) during bidirectional interaction are shown in Fig. 4, depicting a stable breather's signal and corresponding magnitude scalogram in the left panels of Fig. 4A and B, respectively; and a more variable breather's signal and scalogram in the right panels of Fig. 4A and B, respectively. The more stable the breathers were (and hence the lower the variability of the dominant respiration frequency), the more phase-locked they were in the bidirectional interaction ($r^2 = 0.332, p = 0.003$, Fig. 4D); however, there was not a significant association between the variability of the dominant respiration frequency of the participants in the bidirectional condition, and phase locking values in the control-offline condition ($p = 0.069$). There were no associations between the variability of the dominant respiration frequency and in-phase % occurrence ($p = 0.2526$ and $p = 0.1085$, for bidirectional and control conditions, respectively).

There was no significant difference in the confederate's variability of the dominant respiration frequency between the unidirectional interaction ($M = 0.087, SD = 0.025$) and the preceding baseline ($M = 0.092, SD = 0.030$), $p = 0.6155$.

4. Discussion

Our findings demonstrate that real-time interpersonal synchronization of breathing rhythms is facilitated by the emergence of predictable breathing rhythms, rather than online mutual adaptation. Specifically, we find that participants' breathing rhythms are more in-phase synchronized but less phase-locked during the bidirectional versus (online) unidirectional interaction. Moreover, there is no difference in synchronization (in-phase or phase-locking) between the dyads in the online bidirectional interaction and the offline control condition, when a new set of participants coordinate to the replay of participants' respiration rhythms from the bidirectional condition. This suggests that there is no effect of the bidirectional information flow between participants, as long as one participant has engaged in a bidirectional interaction. By testing whether the strength of synchronization is thus related to the emergence of predictable breathing patterns during the bidirectional condition, we find that higher in-phase synchronization and phase-locking in both the bidirectional and offline control interactions are associated with slower breathing rhythms that emerge during the bidirectional condition. Furthermore, we find that the strength of phase-locking, and hence the stability of the synchronization, is associated with the stability of the dominant breathing frequency in the bidirectional interaction.

While these findings are aligned with previous evidence that people are better able at interpersonally aligning their dynamic rhythms in real-time when interacting reciprocally, versus with a designated or forced leader and follower (as we have in the unidirectional condition) (Konvalinka et al., 2010; Noy et al., 2011), they provide new insights into the

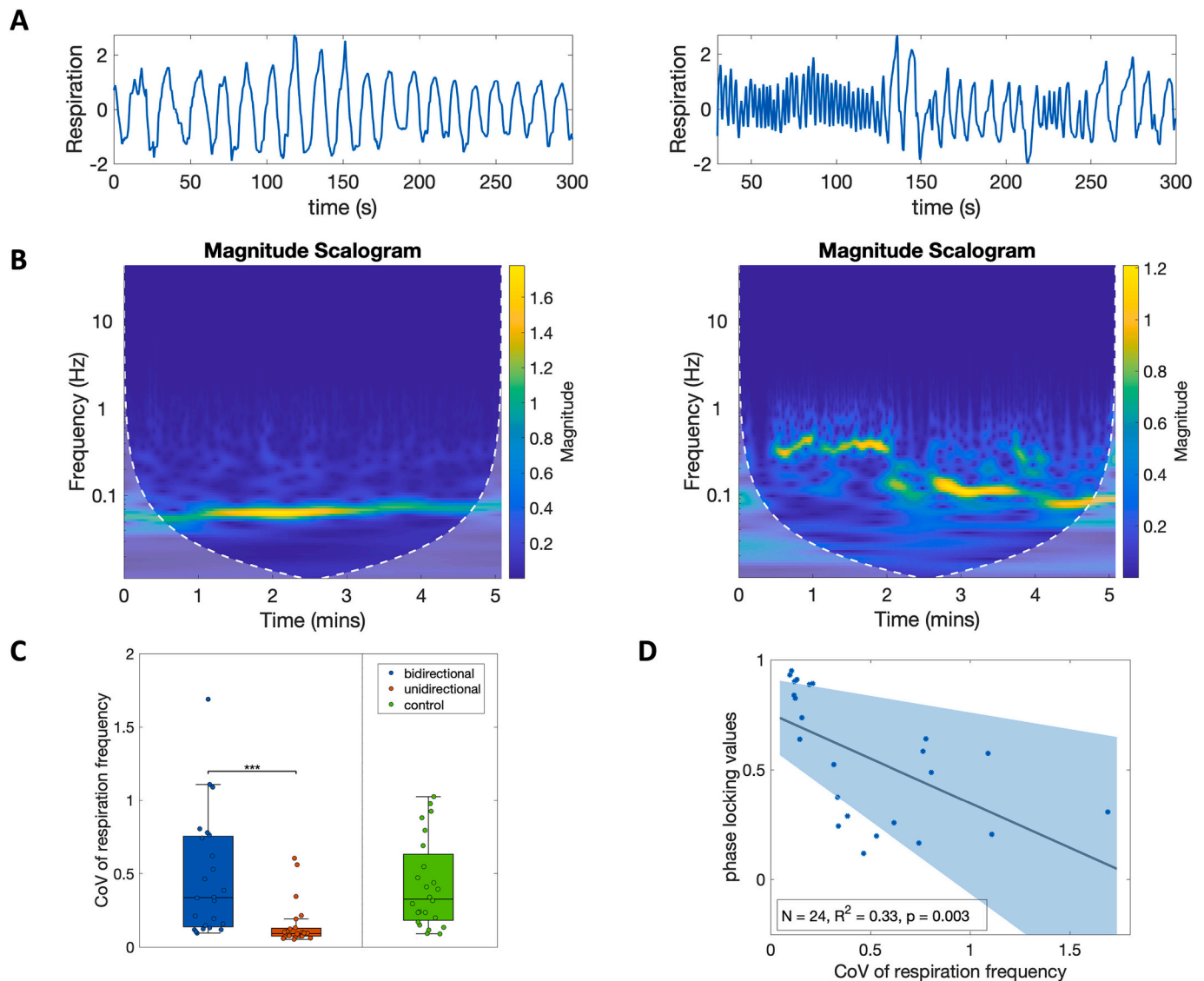


Fig. 4. **A.** Normalized respiration signal of a stable (left panel) and more variable (right panel) breather during bidirectional interactions. **B.** Magnitude scalograms from the wavelet analysis for the stable (left panel) and variable (right panel) breathers in A. **C.** Box plots of the variability of the dominant respiration frequency across the bidirectional, unidirectional, and control conditions. **D.** Linear regression model showing a negative association between the variability of the dominant respiration frequency (across 24 participants, where the first half of interaction is attributed to participant 1 and the second half to participant 2) and phase locking values in the bidirectional interaction, $r^2 = 0.332$, $p = 0.003$. Shaded areas represent 95% confidence intervals.

underlying mechanisms. By testing whether this is an effect of reciprocity or predictability of individual (breathing) rhythms that emerge during interactions, we show with the addition of our offline control condition that reciprocity per se is not what facilitates interpersonal synchronization; rather, the slower breathing rhythms – which represent the real-time predictability of a continuous signal, – as well as the stable breathing frequency – which makes it easier to lock ones' own breathing to, – are associated with better synchronization.

This finding is supported by previous joint action studies showing that people make themselves more predictable when interacting with others. For example, during interactions involving alignment of dynamic movements, people converge on a universal stroke of motion when interacting reciprocally, while they produce unique individual strokes when interacting independently as leaders in a leader-follower scenario (Hart et al., 2014). Moreover, when participants do not have continuous feedback of each other's actions but are required to act in synchrony, they make their (discrete) movements more predictable for the other person (Vesper, van der Wel, Knoblich, & Sebanz, 2011). However, in the case of discrete movements, participants make themselves

predictable by speeding up their movements (Vesper et al., 2011) – a coordination smoother that reduces the variability of their actions (Vesper, Butterfill, Knoblich, & Sebanz, 2010). In contrast, we show here that in the case of continuous and dynamic interactions, people make themselves more predictable by slowing down their breathing, as well as reducing the variability of their breathing frequency. This is supported by previous studies involving continuous movements, which show that people slow down when interacting reciprocally, as well as reduce the variability of their dominant frequency, and increase the smoothness of their movements (Zimmermann, Lomoriello, & Konvalinka, 2022).

While we cannot conclude from the present study whether these movement properties are emergent or intentionally predictable, there is some evidence to suggest that they are either emergent, or a combination of both. Notably, the confederate's breathing patterns were not significantly more predictable during the unidirectional interaction and the preceding baseline. However, while the confederate was aware that participants would be synchronizing to their breathing, they were not told when this would occur – therefore, we cannot conclude from this that there was no intentional attempt to make their breathing more

predictable. In addition, the Zimmermann et al. (2022) study investigated differences between movement properties in individual action (uncoupled from another participant), interactive action (bidirectionally coupled), and observed action (one person improvises continuous movements, while another observes them). The results indicated that while the movement properties of interactive action were more predictable than during individual action, observed action fell between those two conditions. In other words, despite this not being a communicative task, observed actors produced movements that were slower and less variable in their dominant frequency than during individual action, but faster and more variable than interactive action – hence, taking the observer into account in their action plans. This suggests that both emergence and intentionality play a role in the production of predictable movements. However, future research is needed to disentangle the two, by introducing a condition where participants who have no feedback of the other person are aware that another is synchronizing to their movements.

Another question for future research is whether this predictability of movement properties can be found across different modalities (behavioural and physiological), timescales, and coordination tasks that do not rely on the matching of signals (as synchronization tasks do), but complementarity. Recent work has shown that during interaction, temporal dynamics across various modalities (e.g., conversational speech and vocalizations, bodily movements) become coordinated together across a range of timescales (Abney, Paxton, Dale, & Kello, 2014; Abney, Warlaumont, Oller, Wallot, & Kello, 2017; Falk & Kello, 2017; Schloesser, Kello, & Marmelat, 2019), and that this coordination cannot be explained by measures of behavioural similarity or synchronization alone (Abney, Paxton, Dale, & Kello, 2021). This coordination across multiple timescales has been termed complexity matching (Abney et al., 2014), and is thought to maximize information exchange between complex signals (West, Geneston, & Grigolini, 2008), in this case interacting individuals' signals. It would thus be interesting to explore whether people's multimodal signals become more predictable across timescales during more complex interaction tasks.

One finding that is perhaps more surprising is that the participants in this study were more phase-locked during the unidirectional interaction, than when feedback was bidirectional. This is in contrast to previous studies involving coordination of intermittent movements (Gebauer et al., 2016; Konvalinka et al., 2010). However, in contrast to these studies, here we used a confederate in the unidirectional interaction, rather than having the participants take turns at being the “leader”. Given that the confederate produced less variable breathing rhythms (in terms of their frequency), and that phase-locking was associated with the reduction of variability in the dominant breathing frequency, this may explain why participants were more phase-locked in this condition. It would be interesting to follow up on this in future research, and contrast the bidirectional interaction with unidirectional ones between the same participants (in the absence of the third person). Additional manipulations could include informing the participants when they are a leader in the interaction versus when they act alone, i.e., by producing independent rhythms that are not available to the partner, as suggested above.

Finally, we do not find an effect of directionality of feedback (bi-versus unidirectional) on social bonding, i.e., we were not able to induce a higher feeling of affiliation by having participants synchronize their physiological rhythms in real-time reciprocally versus in a unidirectional interaction. There are several possible explanations for this. First, the participants could not see each other, and only synchronized to an arbitrary signal from the other person, which was visually displayed on the screen. It could thus be that there needed to be a stronger feeling of presence of the other person in order to influence the feeling of affiliation. This could be mitigated by having participants interact face-to-face, or in the same room. Second, we contrasted the questionnaire data between different interaction conditions, all which resulted in interpersonal synchronization. Thus, there was no unsynchronized

condition to contrast the scores to. Finally, recent studies show that synchronization alone does not explain affiliation, and that there may be other factors, including complexity and predictability (Ravreby, Shilat, & Yeshurun, 2022). Therefore, we can only interpret this finding as there not being an effect of directionality of feedback on the reports of affiliation.

To summarize, we show in this study that interpersonal synchronization of continuous bodily signals, in this case respiration, is facilitated by the emergence of predictable rhythms – namely, the slowing of one's breathing and the stability of the dominant breathing rate – rather than the reciprocity of interaction. While reciprocity of interaction in this case underlies the emergence of predictable breathing rhythms, it does not have an effect on facilitating the coordination in contrast to interacting offline with the same set of predictable breathing rhythms. People thus become easier to synchronize to when information flow is bidirectional. It would be relevant to further explore whether people also make themselves easier to synchronize to in terms of their breathing when they are aware that someone else is unidirectionally coordinating to them. Finally, we provide a paradigm for inducing interpersonal synchronization of bodily rhythms, which can be used to causally manipulate the strength of synchronization, and study its effects on subsequent social behaviour. This aligns with previous studies that causally manipulate inter-brain synchronization, to study whether it has a functional role in facilitating social interaction (Novembre & Iannetti, 2021; Novembre, Knoblich, Dunne, & Keller, 2017). While we only report the respiration results in this study, our future work aims to also quantify how breathing synchronization affects heart-rhythm synchronization, as well as how interpersonal coordination of physiological rhythms affects one's own intrapersonal cardiorespiratory synchronization. This would provide insight into the physiological mechanisms of self-other integration during interpersonal synchronization.

CRediT authorship contribution statement

Ivana Konvalinka: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Natalie Sebanz:** Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Günther Knoblich:** Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

None.

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