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Intentionality of a co-actor influences sensorimotor synchronisation with a virtual partner

Peta F Mills[1], Bronson Harry[1], Catherine J Stevens[1], Guenther Knoblich[2] and Peter E Keller[1]

Abstract

Interpersonal sensorimotor synchronisation requires individuals to anticipate and adapt to their partner's movement timing. Research has demonstrated that the intentionality of a co-actor affects joint action planning, however, less is known about whether co-actor intentionality affects sensorimotor synchronisation. Explicit and implicit knowledge of a synchronisation partner's intentionality may influence coordination by modulating temporal anticipation and adaptation processes. We used a computer-controlled virtual partner (VP) consisting of tempo-changing auditory pacing sequences to simulate either an intentional or unintentional synchronisation partner. The VP was programmed to respond to the participant with low or moderate degrees of error correction, simulating a slightly or moderately adaptive human, respectively. In addition, task instructions were manipulated so that participants were told they were synchronising with either another person or a computer. Results indicated that synchronisation performance improved with the more adaptive VP. In addition, there was an influence of the explicit partner instruction, but this was dependent upon the degree of VP adaptivity and was modulated by subjective preferences for either the human or the computer partner. Beliefs about the intentionality of a synchronisation partner may thus influence interpersonal sensorimotor synchronisation in a manner that is modulated by preferences for interacting with intentional agents.

Keywords

Interpersonal coordination; intentionality; agency; sensorimotor synchronisation; joint action

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The ability to coordinate movement with others is a human quality often taken for granted. This ability can seem effortless; the way we time a handshake, clap hands in synchrony, or pass a ball to each other—all require little apparent cognitive effort. In fact, the ability to perceive another's actions and then match our own actions in space and time requires the combination of many perceptual, motor, cognitive, and social processes (Konvalinka, Vuust, Roepstorff, & Frith, 2010; Sebanz, Bekkering, & Knoblich, 2006). Previous studies have demonstrated that the mechanisms employed when completing a joint task in cooperation with another actor are different from those when completing a similar task alone. An important aspect of this effect is the knowledge that the co-actor is an intentional agent who means to cooperate to be successful in the joint task. However, little is known about the role of co-actor intentionality during synchronised movement, such as that enacted during musical ensemble performance. Interpersonal synchrony can be considered at several levels, for instance, the level of behavioural performance and the underlying sensorimotor mechanisms that support synchronisation, as well as at a broader social level, such as social cognitive factors and the social context. This study will investigate whether and how social context, specifically implicit and explicit cues of partner intentionality, affects both synchronisation performance and the mechanisms underpinning synchronisation.

[1]Music Cognition and Action Group, The MARCS Institute for Brain, Behaviour and Development, Western Sydney University, Sydney, NSW, Australia
[2]The Social Mind and Body Group, Central European University, Budapest, Hungary

Corresponding author:
Peta F Mills, Music Cognition and Action Group, The MARCS Institute for Brain, Behaviour and Development, Western Sydney University, Locked Bag 1797, Penrith, Sydney, NSW 2751, Australia.
Email: P.Mills@westernsydney.edu.au

The role of co-actor intentionality

Joint action research has shown that when individuals perform an action in partnership with another person, their performance differs to when they perform the task alone (Obhi & Sebanz, 2011). This difference between solo and joint task performance has been attributed to the automatic tendency to form representations of a co-actor's actions and intentions, and to mentally simulate their movements (Sebanz, Knoblich, & Prinz, 2003). Moreover, the mere belief of the presence of an interaction partner can be sufficient to elicit a joint action effect. Several studies (e.g., Atmaca, Sebanz, & Knoblich, 2011; Tsai, Kuo, Hung, & Tzeng, 2008) have found that by manipulating task instructions so participants believed they were performing a task with an unseen other person—as opposed to alone or with a computer partner—resulted in modulation of task performance. These results suggested that participants formed representations about their apparent partner's actions, even though they were in fact never actually interacting with another person.

An important factor that is thought to contribute to the modulation of task performance during joint action is the knowledge that the interaction partner is an intentional agent—a partner that is perceived to be in control of their own actions and consequences, and is capable of sharing the goal to complete a given task together. This has been demonstrated in several studies through the use of inanimate objects (Müller et al., 2011; Tsai & Brass, 2007), non-human agents (Wykowska, Chaminade, & Cheng, 2016), and manipulations of the perceived level of behavioural intentionality of the interaction partner (Atmaca et al., 2011; Stenzel et al., 2012). Variations in performance based on the perceived intentionality of an interaction partner suggest that individuals take into account their partner's goals, and thus modulate their own performance based on the belief their partner is not only intending to coordinate but will do so using similar processes to themselves to achieve the joint goal. This "like me" quality has been associated with an increased tendency to co-represent others' actions (Stenzel et al., 2012; Tsai & Brass, 2007) and to use one's own motor system to simulate others' actions during social interaction (Gallese, 2005; Liepelt & Brass, 2010; Liepelt, Prinz, & Brass, 2010).

These studies of co-actor intentionality have generally used cooperative joint action tasks that assess the cognitive representations of stimulus-response mappings (e.g., the Social Simon task; see Sebanz et al., 2003). However, knowledge about co-actor intentionality may also affect sensorimotor processes that underpin behaviour in tasks requiring real-time interpersonal coordination, as in musical ensemble performance. Experienced music and dance ensembles demonstrate exceptional interpersonal coordination, achieving remarkable temporal precision, while also remaining flexible during dynamic conditions. Furthermore, ensemble performance, by definition, occurs in an interpersonal setting, and social factors such as the intentionality of an interaction partner may therefore also affect the quality of rhythmic coordination (Davidson & Broughton, 2016; Keller, 2014). Such influence has been demonstrated by Kirschner and Tomasello (2009) who found that children's performances improved in a joint drumming task when in a social context, as opposed to drumming with either a drumming machine or a pre-recorded beat. Similarly, at the level of the brain, Novembre, Ticini, Schutz-Bosbach, and Keller (2012) found higher excitability of the motor system when participants believed they were playing a piano piece with another person, instead of in a solo situation, indicating more activation of neural networks that may be involved in motor prediction during joint action. These studies indicate that the joint nature of a task may modulate performance (however, see Welsh, Higgins, Ray, & Weeks, 2007 for a contrary finding). However, these studies do not directly assess if it is the intentionality of the coordination partner that is the modulating factor.

Attribution of a co-actor's agency may be both explicit and implicit (Poonian, McFadyen, Ogden, & Cunnington, 2015). The knowledge that the partner is an intentional agent and overt instructions to coordinate may give rise to an *explicit* belief of a partner's intentionality (as was manipulated in the above studies). Whereas behavioural cues reflecting how responsive a co-actor is may elicit an *implicit* sense of a partner's intention to coordinate. For example, in human-robot interaction studies, it has been found that non-verbal communicative cues that are contingent on the human co-actor's behaviour can lead to robots being perceived as intentional social beings (Breazeal et al., 2016; Gratch, Wang, Gerten, Fast, & Duffy, 2007; Mutlu, Yamaoka, Kanda, Ishiguro, & Hagita, 2009).

Such attribution of intentionality may arise due to the activation of brain regions involved in social-cognitive processing. In a synchronised finger-tapping study investigating the brain bases of dynamic real-time coordination, Fairhurst, Janata, and Keller (2013) employed a virtual partner (VP)—an interactive auditory pacing sequence—set to varying degrees of adaptivity which simulated various levels of cooperativity. The results indicated that distinct neural networks were recruited in response to differences in VP cooperativity. Synchronisation with optimally adaptive VPs, which was stable and judged to be low in difficulty, resulted in activation of midline structures associated with social processes. By contrast, overly adaptive VPs, which yielded less stable performance and higher difficulty judgements, were associated with right-lateralised cognitive control networks. These findings suggest that optimally adaptive, cooperative partners may lead to implicit judgements of partner agency and the intention to coordinate and that the perceived difficulty of the interaction may influence such attributions.

In sum, social factors are an important consideration when investigating interpersonal synchrony. Factors relating to the perceived interaction partner, such as agency and intentionality, may affect coordination performance by influencing the operation of basic mechanisms that support sensorimotor synchronisation. These basic mechanisms include a combination of adaptive and anticipatory processes that may be each affected differentially by judgements of partner intentionality.

Mechanisms underpinning interpersonal synchronisation

Previous sensorimotor synchronisation research has found that collaboration between adaptive and anticipatory processes is what allows people to temporally coordinate actions in a precise yet flexible manner (Keller, Novembre, & Hove, 2014; Mills, Schultz, van der Steen, & Keller, 2015; van der Steen & Keller, 2013). Individuals continuously monitor the joint outcome and adapt their movements to correct for timing errors or accommodate tempo changes, while anticipating what is about to happen in upcoming actions of both self and other. Adaptive timing mechanisms make compensatory adjustments to movement timing to minimise interpersonal asynchronies, whereas temporal anticipation enables the prediction of when a partner's upcoming actions will occur. Both processes have been extensively studied in the context of sensorimotor synchronisation tasks that require participants to tap a finger or strike a drum in time with auditory pacing sequences (for reviews see Repp, 2005; Repp & Su, 2013).

Adaptive timing can be implemented as one of two types of error correction, phase and period correction, which each serve to reduce asynchronies between movements and pacing events during sensorimotor synchronisation. Phase correction is an automatic process that occurs without the conscious awareness of asynchrony and compensates for temporal deviations continuously by adjusting the timing of each movement based on a previous asynchrony, while leaving the rate of an underlying internal timekeeper unchanged (Repp, 2001, 2005). Period correction, on the other hand, is an intentional adjustment of the rate of the internal timekeeper in response to the conscious perception of a tempo change in the pacing sequence (Repp, 2005; Repp & Keller, 2004).

In musical ensemble performance, adaptive timing is simultaneously employed by multiple individuals, each responding to interpersonal asynchronies by adjusting his or her own subsequent actions via temporal error correction (e.g., Goebl & Palmer, 2009; Jacoby, Tishby, Repp, Ahissar, & Keller, 2015; Wing, Endo, Bradbury, & Vorberg, 2014). To investigate such mutual adaptation under controlled conditions, Repp and Keller (2008) employed a computer-controlled VP. The VP works by using a mathematical algorithm that enables the auditory pacing sequence to implement error correction (see Mates, 1994; Repp & Keller, 2004; Vorberg & Schulze, 2002, for details) and thus "interact" with a participant in a manner simulating an adaptive human partner.

When employing error correction during a tapping synchronisation task with a human participant, the computer-controlled VP is programmed to respond to an asynchronous tap by altering the timing of its next tone to account for a proportion of the asynchrony. For example, if the participant taps too early compared to a VP-produced tone, the VP will respond by adjusting the timing of its next tone to sound earlier. The degree to which the VP corrects for timing errors can be prescribed and manipulated such that the computer may simulate either a responsive synchronisation partner (e.g., by employing a moderate degree of phase correction) or a less responsive partner (by employing a lower amount of phase correction). Several empirical studies (e.g., Fairhurst et al., 2013; Mills et al., 2015; Repp & Keller, 2008) have demonstrated that moderate levels of VP adaptivity are best for optimal performance (lower overall asynchrony and variability). By virtue of the VP being more responsive, the more adaptive VP may provide an implicit cue that it is an intentional agent who means to mutually coordinate to achieve the joint goal of synchronised timing.

Conversely to adaptive timing, which acts in a retrospective fashion to enable coordination to be maintained, temporal anticipation allows for accurate prediction of others' future actions. In the case of music performance, this entails the prediction of tempo variations that performers introduce to communicate musical structure, emotion, and aesthetic intentions (Keller, Novembre, & Loehr, 2016). Consistent with claims that action prediction recruits the observer's motor system (Aglioti, Cesari, Romani, & Urgesi, 2008; Kilner, Vargas, Duval, Blakemore, & Sirigu, 2004; Wilson & Knoblich, 2005), it has been argued that the prediction of expressive tempo changes involves action simulation, auditory imagery, and working memory (Colley, Keller, & Halpern, 2018; Keller, 2012; Keller, Knoblich, & Repp, 2007; Pecenka, Engel, & Keller, 2013). Individual differences in these capacities lead to inter-individual variation in anticipatory ability, with some individuals being proficient at predicting tempo changes, while others tend to follow or "track" these changes (Michon, 1967; Mills et al., 2015; Pecenka & Keller, 2009, 2011; Rankin, Large, & Fink, 2009).

To further understand adaptation and temporal anticipation and how these mechanisms interact, van der Steen and Keller (2013) developed the ADaptation and Anticipation Model (ADAM). This computational model consists of three modules that include parameters representing (1) adaptive processes, (2) anticipatory processes, and (3) a "joint internal model" that integrates the adaptive and anticipatory processes. While traditionally studied separately, recent research indicates that temporal adaptation and anticipation are linked. Mills et al. (2015) found a positive correlation between behavioural estimates of temporal error correction and temporal anticipation suggesting that adaptive mechanisms used to correct one's own subsequent movement timing interact with anticipatory mechanisms used to predict other's movement timing. This interaction is instantiated in ADAM's joint module as a process of anticipatory error correction, which involves an adjustment of the timing of planned movements to correct potential synchronisation errors before they occur (van der Steen & Keller, 2013). Specifically, the joint module compares the planned timing of one's next movement (generated by the adaption module) with the predicted timing of a synchronisation partner's movement (generated by the anticipation module) and corrects a proportion of any anticipated discrepancy. To the extent that the joint module provides a seat where planning for self and predictions of other are integrated to enable anticipatory error correction (Keller et al., 2016), this module may be susceptible to the influence of beliefs concerning the perceived intentionality of an interaction partner.

Present study

The present study uses a virtual drumming partner to investigate the role of social context, specifically the effect of explicit and implicit cues as to the intentionality of a synchronisation partner on synchronisation performance and the mechanisms underlying interpersonal synchronisation—namely adaptive timing (period correction), temporal anticipation, and the interaction between the two (anticipatory error correction). To this end, we explicitly instructed pairs of participants to synchronise drumming with each other (i.e., an intentional human partner) or with a computer-generated, tempo-changing sequence of sounds (a deterministic, unintentional partner). In reality, we employed an adaptive VP in both conditions. Thus, when participants are instructed to believe they were coordinating with a human partner, they were in fact, drumming with the VP.

We also provided an implicit cue as to the partner intentionality by varying the degree of adaptivity (phase correction) implemented by the VP to create "low adaptivity" and "moderate adaptivity" partners. To the extent that the VP is more responsive and thus "cooperative" when employing a moderate amount of error correction (Fairhurst et al., 2013), the moderately adaptive partner implies a more intentional partner. These differences in the degree of adaptivity are generally not explicitly detectable and thus represent an implicit cue of the partner's intention to coordinate. While increased adaptivity could also reflect better ability to synchronise, we manipulated the responsiveness of the VP within subjects, with all participants experiencing both the low and moderately adaptive versions for each of the instructed "partners." This design was to ensure that the higher adaptivity of the VP was not viewed as a partner with better ability to synchronise, but rather an increase in responsiveness or intention to coordinate. As the two levels of adaptivity were experienced with each partner, it is presumed that the change in partner responsiveness was perceived not as a result of a change of ability, but rather a change in the intention or commitment to synchronise.

It was hypothesised that performance would be better (reflected in smaller, less variable asynchronies) when participants were told that the VP was a human partner (explicit intentionality cue) and is moderately adaptive (implicit intentionality cue). This effect was expected to be attributable to modulations in the degree of temporal anticipation and anticipatory error correction (as reflected in parameter estimates for the anticipation and joint modules of ADAM, respectively). Assuming that cooperation implies intention and commitment to achieving the joint goal (Michael & Salice, 2017; Michael, Sebanz, & Knoblich, 2016a, 2016b), we predict that more effort will be invested into temporal anticipation and anticipatory error correction if the participant believes that they are interacting with an intentional human partner who is especially cooperative.

The rationale for expecting modulations of temporal anticipation is that interacting with an intentional agent can encourage increased simulation of the partner's actions (Liepelt & Brass, 2010; Liepelt et al., 2010), simulation facilitates anticipatory processes (Aglioti et al., 2008; Kilner et al., 2004; Novembre, Ticini, Schütz-Bosbach, & Keller, 2014), and anticipation leads to better coordination with tempo-changing sequences (Pecenka & Keller, 2009, 2011). Therefore, the increased simulation should allow more accurate prediction (reflected in higher anticipation parameter estimates), and hence better synchronisation when participants believe that the VP is another human. Furthermore, the belief that the partner is "like me" (human rather than a computer) may encourage tighter integration of self and other (Gallese, 2005), leading to an increase in anticipatory error correction parameter estimates in ADAM's joint module.

It was unclear whether partner intentionality would affect temporal adaptation, specifically parameter estimates of period correction. On the one hand, period correction is an intentional process and may be boosted through increased attentional resource allocation (see Repp & Keller, 2004) if the synchronisation partner is perceived to be "like me" from the participant's perspective. On the other hand, period correction is a basic requirement in synchronisation with tempo changes, and may not be affected by beliefs about the source of the pacing signal if the sequence contains tempo changes and the participant aims to perform the task as accurately as possible.

A secondary question was whether individual differences in perceived difficulty to synchronise with each partner would modulate the effect of partner intentionality. We were particularly interested in participants' subjective experiences of interacting with the VP when they were instructed that it was a human versus a computer, as differential preferences or perceptions of the interaction with one type of partner over the other may lead to asymmetrical effects of perceived intentionality. Accordingly, behavioural performance and ADAM parameter estimates may be relatively high in the condition that the participant prefers. Such a finding would add to a growing body of evidence that social-cognitive factors impact upon the mechanisms underlying interpersonal synchronisation (see also Fairhurst, Janata, & Keller, 2014; Novembre, Ticini, Schutz-Bosbach, & Keller, 2012; Novembre et al., 2014; Varlet et al., 2014).

Method

Participants

A total of 64 participants took part in the study (48 females; M=23.3 years, SD=8.06). Fifty-two were undergraduate psychology students from Western Sydney University who participated in return for course credit, and 12 were volunteers who were recruited from the greater Western Sydney area. Fifteen participants had 5 years or more musical experience (M=11.33 years, SD=9.27 years); however, the majority had little to no musical experience (n=49, M=0.5 years, SD = 1.13 years). Participants who recorded insufficient drumming data (n=13; see data analysis for exclusion criteria) were excluded. This was mainly due to the equipment not registering drum strokes that did not have sufficient force and is commensurate with other sensorimotor synchronisation studies (e.g., Mills et al., 2015). In addition, participants who guessed the true nature of the experiment in a post-experiment interview (n=7) were excluded, leaving 44 participants in the final sample. The experiment was approved by the university's human research ethics committee, and all participants provided informed written consent. To avoid disclosure of the true nature of the experiment to other participants during the data collection phase, participants were debriefed in an email after the conclusion of data collection and were given the option to withdraw their data, which was not requested by any participant.

Design

A two-step study design was used, where the first step involved an experimental manipulation of explicit and implicit cues relating to partner intentionality and the second step introduced a post-test measure of subjective partner preference as a covariate. One of the experimental independent variables was the explicit Social Instruction, where participants were instructed to synchronise with either a human interaction partner or a sequence of tones generated by a computer (in reality the participants were always synchronising with the VP). The second experimental independent variable was the VP Adaptivity, with the degree of adaptivity being either low or moderate, which was an implicit cue as to the intentionality of the partner. The third between subjects variable was introduced based on participant's subjective experience of which social condition was easiest. After data collection was completed, participants were divided into three groups depending on whether they reported having found it easier with the "human" partner, the "computer" partner, or if they found the conditions to be the same. It was assumed that the condition participants deemed the easiest would reflect the condition they were most successful in, in regards to synchronisation performance. Based on this, we operationally defined this subjective judgement as "Partner Preference" within this paper. The dependent measures comprised of behavioural measures of synchronisation accuracy (mean absolute asynchrony) and stability (SD of asynchrony, inversely related to stability); as well as modelling estimates from ADAM of each participant's anticipatory and adaptive tendencies, including estimates of period correction, temporal anticipation, and anticipatory error correction.

Materials

There were two identical drumming set-ups in two soundproof booths that were adjacent to a central control room (see Figure 1). In each booth, the drums were placed in front of Cueword teleprompter that was part of a dual video set up. A video camera was attached to the back of each teleprompter to record each participant, which allowed the experimenter to view and record both participants from the control room and for the participants to see each other via a live feed through each teleprompter at specified times. In addition, a Beyerdynamic condenser shotgun microphone allowed a live audio feed, and an Australian Monitor 10 W speaker in each booth allowed the experimenter to communicate verbally with the participants and for the participants to communicate with each other at specified times. The experimenter used an AMX Modero Wired G4 Touch Panel to control the audio and video feeds to regulate when participants could see and hear each other throughout the experiment. All audio and video footage was recorded on Grass Valley Turbo-1 iDDR recording units.

Participants each used a wooden drumstick with a nylon tip to drum on Yamaha DTX TP70 S drum pads, which were held on a metal drum stand in front of the participant. The drum pads were each connected to Roland TD-9 Percussion Sound Modules that were connected to Motu Microlite MIDI interfaces. These were in turn connected to Acer laptops running windows software. A custom-made C + + programme recorded the tapping data as well as presenting the auditory stimuli, which were delivered through

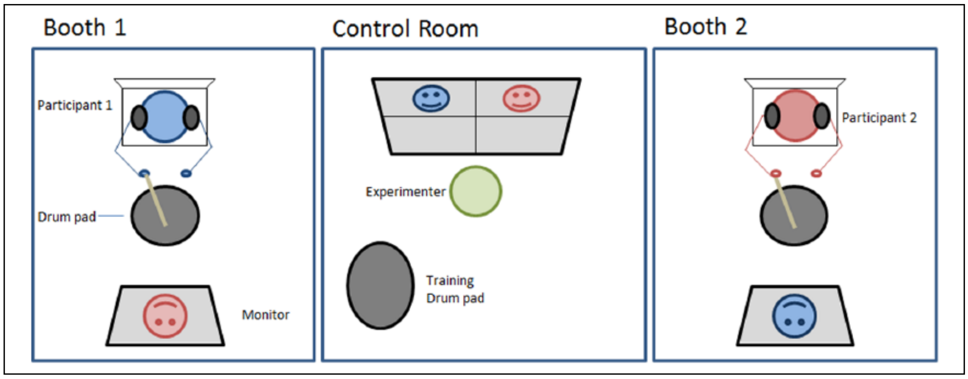

Figure 1. Schematic of the experimental setup. Participants drummed in identical booths adjacent to a control room. Participants were recorded, and a live feed of each participant was displayed to the experimenter (continuously) and to the other participant (between trials only).

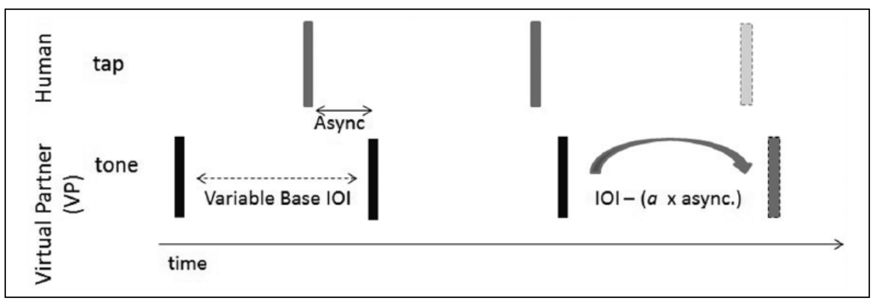

Figure 2. Overview of the adaptive timing mechanism of the virtual partner. Second-order phase correction alters the timing of the subsequent inter-onset interval (IOI) by adjusting for a proportion (*a*) of the asynchrony (async.) between the second-to-last pacing event and corresponding drum tap.

Sennheiser HD650 headphones connected to each of the laptops. End-to-end latency measures taken prior to the experiment revealed a mean delay of 60 ms (SD = 0.9 ms), which was taken into account by the programme. Participants completed initial training and practice trials on a Roland Handsonic 10 percussion pad.

Stimuli

The stimuli were auditory sequences of percussion sounds. Each sequence started with four synthesised cowbell tones, followed by 60 synthesised woodblock tones with clear onset and decay. A beep indicated the end of the trial. The sequences progressed through tempo variations that accelerated and decelerated following a sinusoidal function (as in Mills et al., 2015; Pecenka et al., 2013; Pecenka & Keller, 2011). These sequences varied between 500 and 600 ms with step sizes varying between 1 and 32 ms. This pattern of variation in the sequences was chosen to reflect tempo-changes that resemble those observed during expressive timing in musical performance and were additionally realistic patterns that could be produced by a non-expert human partner.

In addition to these tempo variations, the adaptive function of the virtual partner was applied to implement second-order phase correction (see Figure 2). This adaptive function simulates human phase correction processes by correcting the timing of the subsequent sound by a proportion of the asynchrony between the second-to-last tone and the corresponding tap (see Repp & Keller, 2008). Two levels of adaptivity were used, a = .1 (low adaptivity), and a = .4 (moderate adaptivity), with each value representing the proportion of asynchrony between the tone and the drum tap in the second to last event that was corrected for in the subsequent event. A linear phase correction model based on Vorberg and Schulze (2002) controlled this process with the algorithm

$$t_{n+1} = t_n + T + a \times async(t_{n-1})$$

where t_n is the time of pacing event, T is the base Inter-Onset Interval (IOI; drawn from the tempo changing sequence), a is the phase correction parameter implemented by the computer (.1 or .4), and *async* is the asynchrony between tap and pacing event. For example, if a participant tapped too early (a negative asynchrony) compared to a tone, the second successive event would then occur earlier by a proportion (.1 or .4) of that asynchrony. Thus, each IOI throughout the tempo changing sequence was adjusted in response to the amount and direction of the second to last tap's asynchrony. The present study differs from previous studies that employed the VP in the sense that the current VP algorithm implements second-order, rather than first-order, phase correction.[1]

Procedure

Participants were randomly paired based on the availability of experimental sessions and participant schedules with both participants arriving and being instructed together. They were informed that the purpose of the experiment was to examine how well two people could synchronise with each other while drumming with only auditory information. The participants were shown the two separate rooms and told that their task was to drum in time with each other for half of the experiment, and then, to establish a baseline, they would drum in time with just a sequence of sounds from the computer for the other half of the experiment (counterbalanced). In reality, participants were always drumming with the VP algorithm, and the drumming tasks were identical during each of the different partner instruction conditions.

Before the experimental trials commenced, the participant pairs completed three practice trials together in the central control room where they both drummed simultaneously on a single drum pad in time with a sequence of sounds played through a loudspeaker. These sequences were identical to the tempo changing sequences used during the experimental trials (see Stimuli); however, there was no VP phase correction applied ($a=0$). The participants were asked to note the variation in tempo and were asked to replicate these variations when they were later drumming with each other. Participants were then seated in their respective booths and the doors closed. To reinforce that there was another person doing the experiment, initially, the dual video set up would allow participants to see and hear each other, while the experimenter gave further instructions. This visual and auditory information was turned off during the experimental blocks so that the participants could only hear the auditory stimuli from the computer through their headphones.

Participants completed four blocks of drumming; with each block containing 12 sequences of 60 tones (see Stimuli for details). They were instructed that two of these blocks were baseline recordings where participants would be drumming in time with a computer-generated sequence of sounds, and the other two blocks were joint drumming trials where participants would be drumming with their human partner. For the two blocks within each Social Instruction condition, the VP implemented low adaptivity ($a=.1$) during one block and moderate adaptivity ($a=.4$) during the other. The order of these blocks was counterbalanced and alternated between each condition, with the experimenter informing the participants at the beginning of each block whether they were drumming with their human partner or with the computer. In reality, participants were drumming with the VP during all four blocks.

To reinforce the notion that the drumming task was being completed with a human partner, participants completed a joint problem-solving task between each drumming block. Participants were each given a 5 x 5 grid containing 25 pictures of items in random order. Each grid contained four items that the other participant did not have. By only talking to each other through the speakers in the booth, participants were asked to identify the eight differences between their grids as quickly and accurately as possible. A different set of pictures was used each time the participants completed this task (three times in total). This task was included only as a ruse to maintain the illusion of the joint context and performance data for this task were not analysed.

After all drumming tasks were completed, participants were given a questionnaire to assess whether they believed the experimental instructions and to probe which conditions the participants found easier by including a forced choice question (with response options of "When I was drumming with my partner," 'When I was drumming with the computer' or "It was the same"). Given that participants were interacting with a computer-controlled VP in all conditions, and that all conditions were identical in objective difficulty, this question was assumed to probe subjective preferences for interacting with a human or computer partner. While preferences are not necessarily related to how easy a task is, in the context of a basic synchronisation task, we assume that the partner that is "easier" to synchronise with is the preferred partner. We thus operationally define this judgement of task "easiness" to reflect subjective preferences for interacting with either a human or computer partner.

Data analysis

Data were initially screened for missing taps in Microsoft Excel, and linear interpolation was used to fill gaps left by missing taps and to replace taps that produced a large asynchrony (defined as an asynchrony of $> \pm 250$ ms, which represents half of the smallest target IOI in a sequence). Trials that were missing >3 taps or included three consecutive missing taps were excluded from the analysis. Participants who had four or more trials excluded out of the 12 trials in each condition were removed from the analysis. This criterion ensured that there was sufficient data to generate robust estimates in ADAM.

Data were then processed using MATLAB to obtain measures of synchronisation performance and to generate parameter estimates of period correction, temporal anticipation, and anticipatory error correction using ADAM. Synchronisation performance was assessed in terms of accuracy (mean absolute asynchrony) and stability (*SD* of signed asynchronies). Asynchrony was calculated by subtracting the onset time of the current tap from the onset time of the current tone. Mean absolute asynchrony and *SD* asynchrony were calculated for each individual trial and then averaged across all trials of the corresponding type. Before averaging, a log transformation was applied to absolute asynchronies in each of the four conditions to correct for violations of normality.

Parameter estimates were generated using the version of ADAM ("Joint ADAM Beta") that van der Steen, Jacoby, Fairhurst, and Keller (2015) found to have the best fit to empirical data for sensorimotor synchronisation with tempo-changing sequences. In this version of ADAM, the adaptation module includes a parameter for period correction (β), the anticipation module contains a parameter for temporal anticipation (δ), and the joint module, which connects the anticipation and adaptation modules, contains a parameter for anticipatory error correction (γ) (see van der Steen et al., 2015 for details).

The adaptation module estimates an individual's period correction based on a linear autoregressive error correction model whereby an adjustment is made to the period of the internal timekeeper by a proportion (β), of the most recent asynchrony. The anticipation module generates predictions about the timing of upcoming tones based on the weighted sum of both predictive (extrapolation based on the two previous IOI intervals) and tracking (repeating the previous IOI) processes. An anticipation estimate (δ) of .5 represents that equal prediction and tracking is occurring, whereas values greater than .5 represent relatively more prediction than tracking and values less than .5 represent relatively more tracking behaviour. Finally, ADAM's joint module engages in anticipatory error correction by comparing the output of the adaptation module and the anticipation module and correcting for a proportion (γ) of the asynchrony between the next planned movement and the next predicted sound. When γ is 0, the planned next movement is driven purely by the output of the adaptation model, while the closer γ is to 1, the greater the correction incorporates the output of the anticipation module (the more influence the prediction of the other's timing has over the planned timing of the next movement). Estimates of each model parameter from ADAM were obtained for each participant by fitting the model to the empirical behavioural data from each trial using a bounded Generalised Least Squares method (see Jacoby et al., 2015; van der Steen et al., 2015). These parameter estimates were then averaged across corresponding trials for each participant.

Results

To investigate the effect of the experimental manipulations of Social Instruction (human vs. computer partner) and VP Adaptivity (low vs. moderate adaptivity), as well as the between-subjects factor based on participants' preferences for partner type (prefer human partner, prefer computer partner, no preference), a series of factorial (2 x 2) x 3 analysis of variance (ANOVA) were conducted on each of the dependent measures: mean absolute asynchrony, *SD* asynchrony, period correction (β), temporal anticipation (δ), and anticipatory error correction (γ) estimates. The between-groups factor of Partner Preference was inferred from responses to a post-test questionnaire that assessed subjective judgements of which condition was easiest. The questionnaire revealed that while some participants rated that there was no difference in preferences between the two Social Instruction conditions ($n = 17$), some preferred the apparent human partner ($n = 10$), while others preferred the computer partner ($n = 17$). Prior to these analyses, a preliminary ANOVA on each dependent measure revealed that there was no significant effect of condition order, and no significant relationship between the order of presentation for the Social Instruction condition and judgement about which condition was preferred. All effects are reported as statistically significant at $p < .05$.

Synchronisation accuracy and stability

Contrary to our main hypothesis, the analysis of log-transformed mean absolute asynchrony (Figure 3a, shown untransformed) revealed that there was no significant main effect for Social Instruction, $F(1, 41) = 0.10$, $p = .92$, $\eta_p^2 < .001$. The belief that one is interacting with a human rather than computer apparently did not reliably increase overall synchronisation accuracy. There was, however, a significant main effect of VP Adaptivity, $F(1, 41) = 22.66$, $p < .001$, $\eta_p^2 = .356$, with the low adaptivity condition displaying higher asynchrony than the moderate adaptivity condition, suggesting better overall joint performance when the VP was more adaptive. There was no main effect of Partner Preference $F(2, 41) = 1.22$, $p = .31$, $\eta_p^2 = .056$, and no significant interaction between Social Instruction and VP Adaptivity, $F(1, 41) = 1.92$, $p = .17$, $\eta_p^2 = .272$. There was, however, a marginally significant two-way interaction between Social Instruction and Partner Preference, $F(1, 41) = 3.22$, $p = .05$, $\eta_p^2 < .136$, and a significant three-way interaction between VP Adaptivity, Social Instruction, and Partner Preference, $F(2, 41) = 4.92$, $p = .012$, $\eta_p^2 = .193$ (see Figure 3). As Partner Preference was included as a post hoc variable, we also conducted a Bayesian analysis (calculated using JASP software, Version 0.8.6) to test the integrity of this interaction. The Bayes factor for the full model including the three-way interaction was BF10 = 15.538, whereas the Bayes factor for a model without the interaction term

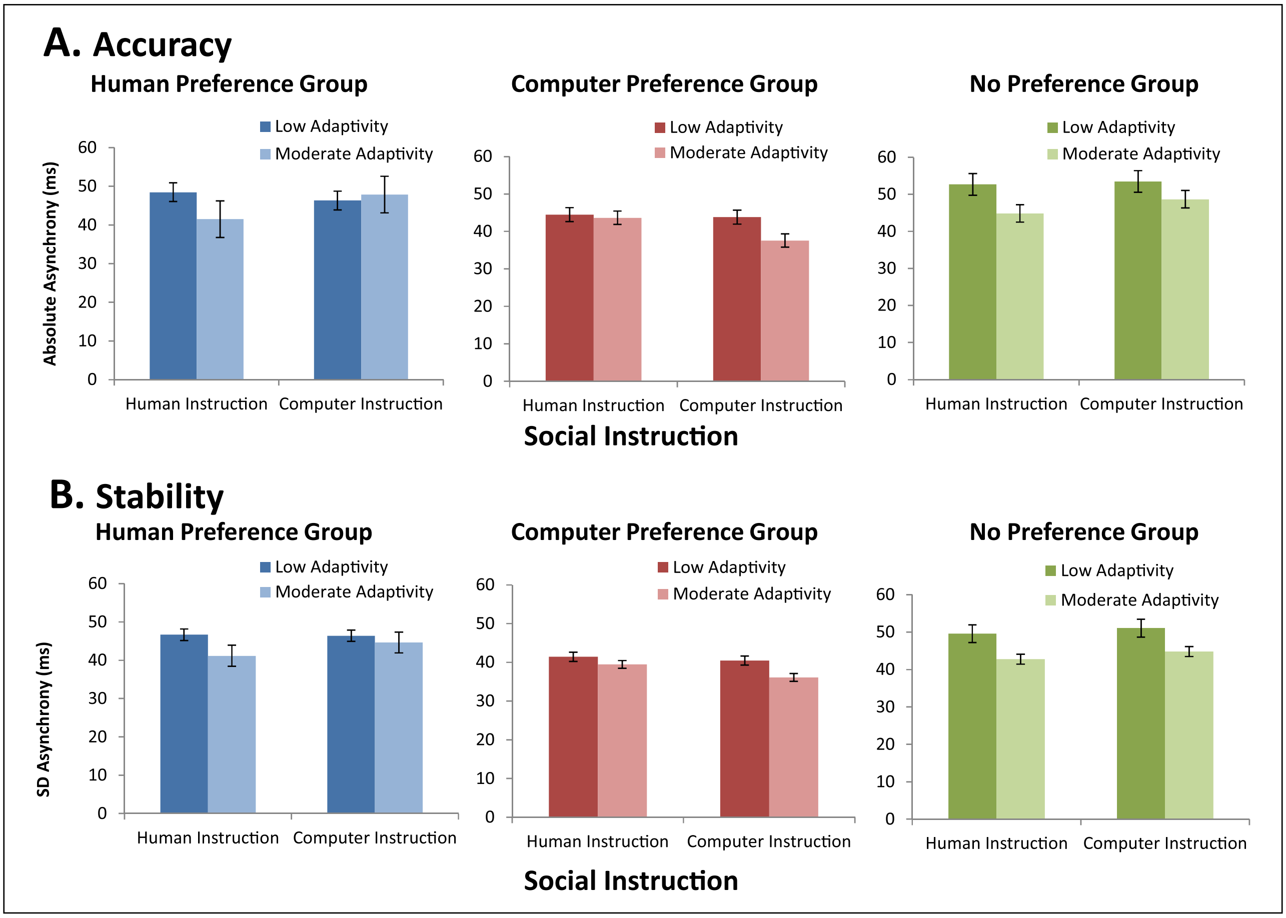

Figure 3. Measures of synchronisation performance split between low VP Adaptivity and moderate adaptivity for the three partner preference groups. Panel a—Accuracy (Mean Absolute Asynchrony, untransformed) and Panel b—Stability (*SD* Asynchrony). Error bars represent SEM as calculated using the repeated measures method suggested by Franz and Loftus (2012).

included was BF10 = 6.829. The inclusion Bayes factor based on matched models that directly compares these two models was 2.275, which can be interpreted to indicate that the data are more than twice as likely under a model with this interaction term as under a model without this interaction term.

These interactions were unpacked by performing analyses separately for each Partner Preference group. A series of one-tailed dependent *t*-tests were conducted to compare synchronisation accuracy between the two levels of adaptivity for each of the different social instruction conditions. One-tailed tests were chosen because of the directional hypothesis that performance accuracy would improve (lower asynchronies) in the moderately adaptive condition compared to the low adaptivity condition. For the human preference group, accuracy was significantly better when drumming with the moderately adaptive partner only during the human instruction condition, $t(9) = 2.04$, $p = .036$, and not when instructed that the partner was a computer, $t(9) = -.47$, $p = .676$. Likewise, the computer preference group showed significant improvement in accuracy with the moderately adaptive partner only during the computer partner instruction, $t(16) = 3.99$, $p < .001$, and not the human partner instruction, $t(16) = .80$, $p = .22$. Whereas the no preference group showed significantly higher more accuracy with the moderately adaptive partner during the human instruction condition, $t(16) = 4.52$, $p < .001$, and approached significant improvement during the computer instruction condition, $t(16) = 1.71$, $p = .053$.

The analysis of the *SD* asynchrony (Figure 3b) revealed no significant main effect of Social Instruction, $F(1, 41) = 0.19$, $p = .66$, $\eta_p^2 = .005$, a significant main effect of VP Adaptivity, $F(1, 41) = 26.40$, $p < .001$, $\eta_p^2 = .39$, with the low adaptivity condition displaying greater variability than the moderate adaptivity condition), and no main effect of Partner Preference, $F(1, 41) = 2.57$, $p = .09$, $\eta_p^2 = .111$. There were also no significant interactions (all $p > .05$), however, the general trend for the data reflected that found in the accuracy data (see Figure 3).

Model-based parameter estimates of underlying mechanisms. All model-based parameter estimates are presented in Table 1. There were no significant effects (all $p > .05$) in

Table 1. Average parameter estimates generated by the ADaptation and Anticipation Model (ADAM) for period correction (β), anticipation (δ), and anticipatory error correction (γ) for the Social Instruction and VP Adaptivity conditions for each Partner Preference group.

Condition			Parameter estimates					
Preference group	Social instruction	Adaptivity	Period correction (β)		Anticipation (δ)		Anticipatory error correction (γ)	
			M	*SE*	*M*	*SE*	*M*	*SE*
Human	Human	Low	0.114	0.036	0.052	0.020	0.616	0.051
Preference		Moderate	0.098	0.022	0.042	0.022	0.630	0.048
(*n* = 10)	Computer	Low	0.125	0.027	0.056	0.024	0.620	0.054
		Moderate	0.099	0.023	0.050	0.024	0.564	0.054
Computer	Human	Low	0.175	0.041	0.061	0.021	0.677	0.026
Preference		Moderate	0.137	0.030	0.017	0.006	0.637	0.030
(*n* = 17)	Computer	Low	0.123	0.019	0.058	0.015	0.668	0.026
		Moderate	0.134	0.019	0.019	0.007	0.663	0.024
No	Human	Low	0.088	0.016	0.064	0.019	0.570	0.035
Preference		Moderate	0.079	0.013	0.032	0.014	0.554	0.039
(*n* = 17)	Computer	Low	0.100	0.023	0.085	0.035	0.572	0.038
		Moderate	0.100	0.024	0.046	0.019	0.537	0.040

the analysis of period correction (β), which indicates that temporal adaptation was applied similarly across all conditions. For the anticipation parameter (δ), the estimates were quite low overall. Given that a value of 0.5 indicates an equal amount of predicting and tracking, the relatively low observed values indicate that participants had a stronger tendency to track rather than to predict the tempo changes in all conditions. The ANOVA on anticipation estimates revealed no significant effect of Social Instruction, $F(1, 41) = 0.55$, $p = .461$, $\eta_p^2 = .013$, but there was a significant effect of VP Adaptivity, $F(1, 41) = 7.33$, $p = .01$, $\eta_p^2 = .152$, with the moderately adaptive condition associated with more tracking/less predictive behaviour than the low adaptivity condition. There was no significant main effect of Partner Preference, $F(2, 41) = .60$, $p = .56$, $\eta_p^2 = .028$, nor were there any significant interactions (all $p > .05$).

The analysis assessing anticipatory error correction (γ) revealed no significant main effect of Social Instruction, $F(1, 41) = 1.69$, $p = .20$, $\eta_p^2 = .039$, but again a significant effect of VP Adaptivity, $F(1, 41) = 13.92$, $p < .001$, $\eta_p^2 = .253$, with participants employing more anticipatory error correction during the low adaptivity condition than during the moderately adaptive condition. This means that there was a greater influence of the anticipated timing of pacing sequence over the planned timing of the next tap when the VP was less cooperative. There was no significant effect of Partner Preference, $F(2, 41) = 2.41$, $p = .103$, $\eta_p^2 = .105$, but there was a significant three-way interaction between Social Instruction, VP Adaptivity, and Partner Preference, $F(2, 41) = 5.47$, $p = .008$, $\eta_p^2 = .211$. There were no other significant interactions, (all $p > .05$).

Similar to the accuracy results, the three-way interaction was analysed by conducting a series of dependent *t*-tests separately for each preference group, to compare anticipatory error correction at each level of VP adaptivity. For the human preference group, there was significantly less anticipatory error correction when drumming with the moderately adaptive partner during the computer instruction condition, $t(9) = 3.53$, $p = .006$, but not when instructed that the partner was a human, $t(9) = -.51$, $p = .625$. Likewise, the computer preference group showed significantly less anticipatory error correction in the moderately adaptive partner condition, however, only with the human partner instruction, $t(16) = 2.88$, $p = .011$, and not the computer partner instruction, $t(16) = .44$, $p = .67$. Similar to the human preference group, the no preference group showed significantly less anticipatory error correction with the moderately adaptive partner during the computer instruction condition, $t(16) = 2.98$, $p = .009$, but not with the human partner instruction, $t(16) = 1.15$, $p = .028$.

Discussion

To investigate the effect of partner intentionality on interpersonal sensorimotor synchronisation and its underlying mechanisms, participants were asked to drum in time with either a computer or a human partner (an explicit social instruction relating to partner intentionality). In reality, participants were always drumming in time with a computer-controlled VP that simulated either a less adaptive or a moderately adaptive partner producing tempo-changing sequences (an implicit cue to partner intentionality). Overall, synchronisation performance improved (both synchronisation accuracy and stability) with the moderately adaptive VP which was simulating a more responsive partner that implied an intention to coordinate; however, there was no direct effect of the explicit social instruction on synchronisation performance and its underlying mechanisms. Yet, once individual differences in partner preference were taken into account, effects emerged relating to the explicit social instruction, and these effects were dependent on the responsiveness of the VP.

There was a significant improvement in performance when the VP was more adaptive and implied an intentional partner. This suggests that when the VP was more adaptive and thus more responsive, participants modulated their performance to maximise the joint outcome. It appears that an implicit sense that a co-actor is actively contributing in a synchronisation task leads to adaptation of one's own motor behaviour. This modulation in performance may occur because synchronisation with a more adaptive partner leads to a sense of a co-actor's commitment and willingness to cooperate, resulting in more individual effort being applied to the joint task. Because we employed a within-subjects design, we can infer that an increase in VP responsiveness was interpreted as changes in intention to coordinate rather than a partner with better ability to synchronise. However, further research into the way synchronisation behaviour is modulated when an individual takes into account both a partner's intentions and their ability will be an important next step and may be investigated using the VP with a between subjects design.

In contrast to the findings in regards to VP adaptivity, there was a lack of a direct influence of Social Instruction, which suggests that independent of explicit beliefs as to whom the interaction partner was (human or computer), performance was similar in terms of synchronisation accuracy and stability. Together, the results relating to the implicit cue of VP Adaptivity and the explicit Social Instruction, demonstrate not only the importance of implicit behavioural cues during a joint task, but also the dissociation between implicit and explicit cues as to partner intentionality, and suggest that implicit cues could be more influential in the context of interpersonal synchronisation.

Although the explicit cue of partner intentionality had no direct effect on synchronisation performance, once individual differences for partner preference were considered, a more nuanced picture emerged for synchronisation accuracy. Depending on which apparent partner was preferred, there was an interaction between the implicit cue of VP adaptivity and the explicit Social Instruction. The accuracy results showed that for those who reported preferring to coordinate with one partner or the other, performance was significantly better when the VP was moderately adaptive, but only when instructed to drum with the partner that was congruent with their personal preference, and not with the partner that was incongruent with their preference. This was despite the moderately adaptive condition being identical during both social instruction conditions. When these participants were told they were synchronising with their non-preferred partner, their performance did not improve with the moderately adaptive VP, even though the VP was correcting for a greater amount of asynchrony and an improvement was to be expected (see Fairhurst et al., 2013; Repp & Keller, 2008). This lack of improvement suggests that when synchronising with a partner who is not the preferred partner, individuals resist the aid of the more adaptive VP to the detriment of improved performance. It may be that a pre-existing belief or bias against a particular type of partner is triggered by the explicit instruction and can override the implicit sense of cooperativity, which would otherwise lead to improved joint performance.

Those individuals that reported no preference for either of the partner types showed similar improvements in performance with the more adaptive VP during both Social Instruction conditions. The results relating to what we have labelled as "preference" suggests that pre-existing ideas or stereotypes about how responsive or predictable a partner of a particular type is, may influence the way an individual approaches a joint synchronisation task. For instance, general understanding of the way computers work may lead to an assumption that the computer will not be adaptive or responsive and thus the perception may be that synchronisation will be more difficult. Alternatively, a computer may be perceived as more stable and predictable and thus easier to synchronise with. Likewise, a human may be thought to be more cooperative and thus easier to synchronise with, or may be viewed as unstable and less predictable and thus may be judged to be more difficult to synchronise with. These findings extend existing evidence that top-down processes play a role in action co-representation during joint action (e.g., Brown & Brüne, 2012; Liepelt & Brass, 2010; Stenzel et al., 2012).

Indeed, the post hoc grouping of participants according to preferences is an exploratory factor, and definitive inferences cannot be drawn. Nevertheless, the pattern of results suggests that individual differences in personal preference for a synchronisation partner may modulate the interaction between explicit beliefs and implicit beliefs about a partner's intention to coordinate during a sensorimotor synchronisation task. These results thus provide some initial evidence that individual differences in social attitudes may modulate performance during a joint action.

Concerning the mechanisms that underpin synchronisation, the implicit and explicit manipulation of intentionality had different effects on indices of each of the mechanisms (i.e., ADAM parameter estimates). In regards to period correction, there were no differences found between the conditions, indicating that individuals employed adaptive timing equally when synchronising, despite the apparent partner or the degree of adaptivity employed by the VP. In contrast, similar to the observed differences in synchronisation performance with the implicit cue of partner intentionality (VP Adaptivity) there were differences in the other underlying mechanisms of synchronisation performance—temporal anticipation and anticipatory error correction. First, there was relatively more tracking behaviour (less anticipation), and second, less anticipatory error correction, when the VP was moderately adaptive. In contrast to our predictions, this indicates that people reduce their effortful predictive processes when the synchronisation partner takes on more of the adaptive burden. In light of greater synchronisation accuracy and stability when the VP was moderately adaptive, these results suggest that participants may have put less effort into temporal anticipation when the partner evoked a greater sense of intentionality by being more cooperative.

Similarly, the lower anticipatory error correction estimates when the VP was more cooperative indicates that participants corrected for a smaller proportion of the difference between the output of the adaptation module (their estimate for self) and the anticipation module (their prediction of other). This suggests that when there is implicit information about co-actor intentionality, the contribution of the partner is recognised and an individual may opt to rely more so on the more responsive partner to contribute to the joint performance in a form of social loafing (see Karau & Williams, 1993). In addition, with the implicit sense of a responsive intentional partner, it may be assumed that the co-actor has the ability to take a follower role, which is not the case with an unintentional, unresponsive partner. Perhaps participants are more inclined to allow the balance of leading and following to shift between themselves and their partner when their partner is more responsive, requiring less active anticipation and anticipatory error correction. This may be tested in future experiments by explicitly instructing participants to lead or follow their partner while varying the adaptivity of the VP.

As with synchronisation performance, there was no direct effect of the explicit Social Instruction on the underlying mechanisms of synchronisation. However, similar to the accuracy results, once individual subjective preferences were taken into account, the explicit social instruction was found to modulate the effect of VP adaptivity on anticipatory error correction. Specifically, when the VP was moderately adaptive compared to less adaptive, participants engaged in significantly less anticipatory error correction, but only during the Social Instruction that was incongruent with their preferred partner. This suggests that when the VP was more adaptive participants were less likely to integrate their prediction of their partner's timing into their own planned next movement when instructed that they were synchronising with the non-preferred partner.

Given that the higher adaptivity and thus cooperativity of the VP was more likely to invoke a sense that the partner is "like me" (Gallese, 2005) and is committed to achieving the joint goal to synchronise (Michael et al.,2016a, 2016b), more integration between self and other (reflected in larger anticipatory error correction estimates) was expected. However, perhaps those who preferred one partner to the other did not interpret the higher adaptivity as "cooperative" or "like me" when the explicit instruction led them to believe that the partner was not the preferred synchronisation partner. In this instance, rather than accepting the increased contribution of the partner as helpful, these participants may instead have inferred the higher adaptivity as being less stable and thus less predictable (also see Fairhurst et al., 2013) and therefore reduced the degree that their predictions of the partner's timing influenced their own subsequent movement timing.

Overall, the results of this experiment suggest that during synchronisation, implicit cues of partner intentionality are more influential than explicit cues. However, for some, explicit cues may take precedence when the implicit cues are incompatible with prior beliefs about how a particular partner should behave. This may resonate with Bayesian inference processes where the influence of priors becomes stronger when the available evidence is less reliable (Elliott, Wing, & Welchman, 2014; Ernst & Bülthoff, 2004). In our case, prior knowledge of how an intentional or an unintentional synchronisation partner behaves may influence beliefs about how responsive an interaction partner should be. These priors are activated by the explicit social instruction and then compared to the currently available evidence—the actual responsiveness of the partner (the degree of VP adaptivity). For those who may have stronger pre-existing expectations (or priors), the influence of the explicit instruction may be assigned greater weighting when the actual responsiveness of the VP is incompatible or contradictory to these priors. This could be further investigated by making the available evidence less reliable, for instance, increasing the variability of the VP by employing large degrees of adaptation that render the partner uncooperative (e.g., Fairhurst et al., 2013).

When interpreting the overall results of this study, the fact that participants had such different views as to which apparent partner was preferred, is of itself noteworthy. Both conditions were identical so it was expected that the majority of participants would find both conditions equally difficult. However, a majority of choices made were directional towards one "partner" as being easier than the other. These differences in post-task subjective preference may have been driven by participants' sensitivity to their performance being better in one condition over the other. However, based on the results of the current study, it is not possible to know what drove this preference choice. It may be that better synchronisation with the belief of a particular type of partner (human or computer) resulted in a preference for that partner OR a preference for a particular type of partner led to better synchronisation with that partner. Either way, there was an effect of social instruction that differed depending on individual differences in partner preference. Which of these options is the explanation for the effect is still an open research question. This issue may be addressed in future research by a priori assessment of the type of interaction partner that is preferred (intentional or unintentional).

Nonetheless, of particular interest here is why, when the VP was more adaptive, the differences in accuracy and anticipatory error correction occurred depending on partner preference. It could be that pre-existing notions about which type of partner will be easier to work with, or a general preference for interacting with either an intentional or unintentional partner, may create a bias that then modulates the way one synchronises. Despite previous work showing that performance on a joint task differs depending on the belief of an intentional partner (e.g., Liepelt et al., 2010), this effect may be nullified when the responsiveness of the partner seems to be incompatible with pre-existing ideas about that partner's ability or competence. In this case, resistance to that partner's contribution may occur despite believed intentionality. For instance, those who preferred the computer partner may have perceived their apparent human partner as a more unpredictable partner and thus when the VP was more adaptive, the increased variability was perceived as instability rather than a cooperative partner that is aiding with synchronisation.

In conclusion, the intentionality of a synchronisation partner does affect performance during an interpersonal sensorimotor synchronisation task; however, in general, implicit cues as to the intentionality of the partner appear to be more influential than explicit cues. This effect is also reflected in two of the underlying mechanisms of synchronisation, where people engage in less temporal anticipation and anticipatory error correction with a more adaptive partner. This indicates that people are more inclined to reduce the effortful allocation of resources when coordinating with a partner who behaves in a responsive manner. Second, individual differences in preference for synchronising with an intentional agent vs a static computer may interact with explicit instructions about who the interaction partner is. These differences were demonstrated for synchronisation accuracy and were further reflected within the underlying mechanism of anticipatory error correction, where it is proposed that the integration between self and other occurs (van der Steen & Keller, 2013). Taken together, this demonstrates that when investigating the role of partner intentionality on interpersonal behaviour, it is essential not only to consider characteristics of the interaction partner but also to take into account individual differences in social preferences or biases as potential modulating factors.

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Note

1. Previous research on phase correction has found evidence that second-order phase correction supplements first-order correction under certain conditions in sensorimotor synchronisation tasks, including at relatively fast tempi (Repp, Keller, & Jacoby, 2012; Semjen, Schulze, & Vorberg, 2000) and with high task demand and expertise (Pressing, 1998). Pilot testing revealed that synchronising with sequences that are both adaptive and include tempo-changes qualifies as a demanding task and, furthermore, that the tendency for participants to "overshoot" at tempo-change transitions (fast-to-slow and slow-to-fast turning points) raises questions about whether first-order correction is the best option at these points. In any case, to justify the use of second-order phase correction in the present experiment on empirical grounds, we conducted an additional experiment (Mills & Keller, in prep.) to compare the effects of first-order versus second-order phase correction on behavioural performance and parameter estimates obtained for sensorimotor synchronisation with tempo-changing VPs. This additional experiment revealed that, while the *SD* of asynchronies was higher for sensorimotor synchronisation with VPs that implemented second-order correction than for first-order correction (as could be predicted based on Vorberg & Schulze, 2002), all other measures including the parameter estimates of interest in the present experiment were commensurate for first-order and second-order correction. We therefore expect that results would generalise to contexts where first-order correction is employed.

ORCID iD

Peta F Mills https://orcid.org/0000-0001-7393-7193

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