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Current Opinion in Behavioral Sciences

# Modelling single-person and multi-person event-based synchronisation

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A linear phase correction model has been shown to accurately reflect the corrective processes involved in synchronising motor actions to an external rhythmic cue. The model originated from studies of finger tapping to an isochronous metronome beat and is based on the time series of asynchronies between the metronome and corresponding finger tap onsets, along with their associated intervals. Over recent years the model has evolved and been applied to more complex scenarios, including phase perturbed cues, tempo variations and, most recently, timing within groups. Here, we review the studies that have contributed to the development of the linear phase correction model and the associated findings related to human timing performance. The review provides a background to the studies examining single-person timing to simple metronome cues. We then further expand on the more complex analyses of motor timing to phase and tempo shifted cues. Finally, recent studies investigating inter-personal synchronisation between groups of two or more individuals are discussed, along with a brief overview on the implications of these studies for social interactions. We conclude with a discussion on future areas of research that will be important for understanding corrective timing processes between people.

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## Introduction: variability of timing

Rhythmic action with periodic movements that are maintained in synchrony with others or with regulated phase across group members is a common feature of various human activities. For example, in a rowing eight, at a rate of 30–40 strokes per minute, the rowers attempt to bring the blades of their oars into the water at the same time to achieve a good ''catch''. This is followed by a concerted pull to drive the boat through the water [1]. In music ensembles, at tempos ranging from 50 to 200 beats per minute (bpm; largo — prestissimo), the players strive for a common pulse so that notes scored as simultaneous sound together across the different instruments [2••]. In dance, the performers not only move in time to the music but must also synchronise among themselves [3]. The question addressed in this review is, how do individual participants engaged in such activities adjust their relative timing to achieve synchrony with other individuals within the group?

Biological timing is inherently variable and affected by fluctuations in produced intervals which, for instance, in simple tapping tasks, increase with duration [4,5]. As a result, even if the various members of an ensemble start exactly together and agree on the same target interval (tempo or rate), individual timing variability means the members of the ensemble will inevitably slip out of phase with one another during the course of a performance. To compound the problem, tempo change is often called for during performance (e.g. slowing at the end of a piece of music). As a result, differences in the control of the rate of tempo change by each individual will further add to the tendency to develop differences in phase. Active adjustment of timing is therefore required to keep the players' phase differences close to zero. In this paper, we review how adaptive feedback and predictive feedforward mechanisms operate in support of interpersonal timing. We start by considering one person synchronising with a fixed or an adaptive metronome. The event-based timing models that have been used to describe correction mechanisms for an individual to maintain synchrony with a metronome, are defined. We then turn to the case of groups of two or more individuals synchronising with one another. Tasks discussed in this review include finger tapping, arm movement, musical performance, and rowing.

## Synchronisation with a fixed metronome

Perhaps the earliest published demonstration of the variability in individual periodic timing is that of Stevens [6]. Participants tapped a Morse code key, first in time to a metronome then unpaced, at rates in the range of 60–150 bpm on different trials. The time intervals between consecutive unpaced taps (termed interresponse intervals, or IRIs) exhibited variability that increased with IRI duration. Stevens characterised the fluctuations in IRI as comprising short and long term components which have been linked to separate peripheral movement implementation and central timekeeping processes respectively [4]. The peripheral component, $M_n$, adds jitter to the time of the $n$th movement implementation event (response), causing negative covariation between successive IRIs [7]. In terms of paced tapping, it is the central timekeeper interval, $T_n$ and its variability, $\sigma_T^2$, that determine synchronisation accuracy with the metronome. Timekeeper variability tends to increase with longer interval durations, whereas motor variability, $\sigma_M^2$, remains at a relatively small value [7–9].

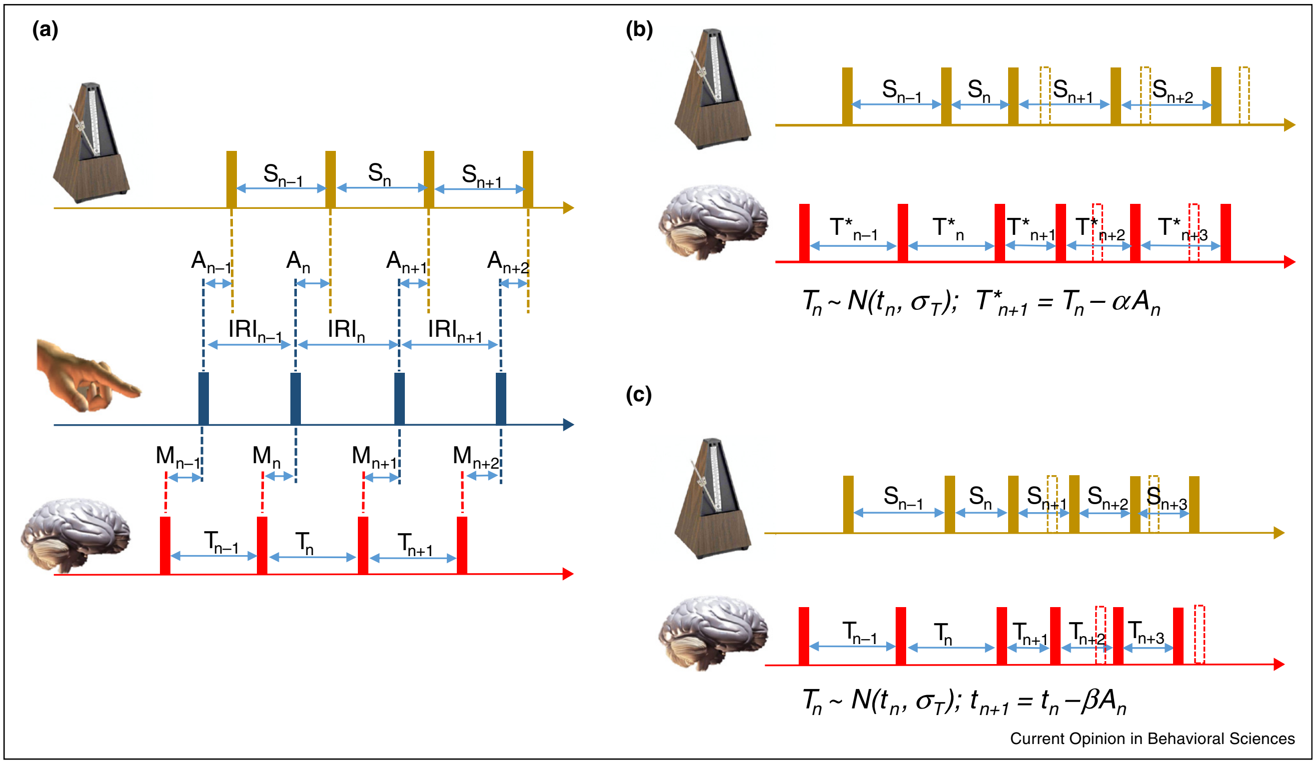
The ability to synchronise with a metronome (for reviews see [10,11•]) despite the presence of variability in timed periodic movement, implies feedback correction. Vorberg and colleagues proposed a first-order linear phase correction model, in which the asynchrony between the finger tap and related metronome pulse is used to effect a proportional correction of the time to the next tap [12,13]; see Eq. (1).

$$A_{n+1} = (1-\alpha)A_n + T_n + M_{n+1} - M_n - S_n \tag{1}$$

where $\alpha$ is the correction gain, $A_n$ is the current event asynchrony, $T_n$ is the time interval generated by an assumed internal timekeeper, $M_n$ is the current motor implementation delay, and $S_n$ is the current metronome interval (see Figure 1a).

If the correction gain, $\alpha$, lies between 0 and 2, Eq. (1) results in stable performance in the sense that a synchronisation error at tap $n$ is progressively reduced over successive taps, $n + 1$, $n + 2$, etc. Here, we focus the review on this linear phase correction approach, where

**Figure 1**



**(a)** Schematic of the two level timing model. We assume that when participants tap in time to a metronome (with interval, $S$, shown in brown) the observed variance in the asynchronies ($A$) and inter-response intervals (*IRI*, blue) is a result of the variance in the timekeeper intervals ($T$, red) and the motor delays ($M$). Because of the resulting variance, a correction mechanism must be implemented to adjust for the error made on the preceding tap. This correction is applied to the timekeeper in two ways, phase and period correction. **(b)** A *phase correction* is applied to the timekeeper to adjust the relative phase between finger tap events (not shown) and the metronome beats. The correction is made to the timekeeper interval, $T_n$, which is sampled from a normal distribution with mean interval $t_n$ and standard deviation, $\sigma_T$. The amount of correction is based on the last asynchrony ($A_{n-1}$) multiplied by a correction gain, alpha ($\alpha$). A full correction of the last asynchrony therefore occurs when $\alpha = 1$. Correction is stable in the range of $0 \leq \alpha \leq 2$. A forced phase-perturbation (as shown by the shortening of interval $S_n$) can be used to observe explicit phase-correction responses. The dashed onsets indicate where the beats would be expected to occur without the perturbation. Note that the underlying timekeeper interval is not changed; rather, a correction is applied to each interval. **(c)**. A *period correction*, $\beta$, is applied to the timekeeper when a change in the tempo of the metronome beat occurs. An abrupt tempo change can be used to explicitly observe period correction as shown with intervals $S_n$ to $S_{n+2}$. The dashed onsets indicate where the beats would be expected to occur without the perturbation. Note that in contrast to phase correction, a period correction changes the underlying mean timekeeper interval, $T_n$. In many cases, phase and period corrections will occur in parallel.

movement corrections are performed within this stable range. An alternative method to analysing synchronisation is the non-linear dynamical systems (NLDS) approach. Characteristics of the NLDS approach include a focus on instability and an emphasis on the continuous nature of behaviour. A comparison of linear phase correction and NLDS approaches may be found in Pressing [14].

It can be shown that corrections based on Eq. (1) produce a characteristic asynchrony autocovariance function (AACF). The AACF exhibits a negative value at lag one damping towards zero with increasing lag if $\alpha$ lies between 0 and 1 (over-damped). In contrast, it oscillates between negative and positive values while damping to zero if $\alpha$ lies between 1 and 2 (under-damped). The value of $\alpha$ that minimises asynchrony variance is considered optimal and results in an AACF that is zero beyond lag 1 (critically damped). This occurs when $\alpha = 1$, dropping to slightly less than 1 when there is appreciable motor implementation variability. Vorberg and Schulze [13] developed an estimation procedure based on numerical minimisation to fit the AACF of the experimental asynchronies to the model's predictions. However, the accuracy of this method is limited by estimation bias and parameter interdependence when the estimated $\alpha$ values are close to optimal. Jacoby and colleagues [15] showed that these problems can be avoided by assuming that the motor variance is smaller than the timekeeper variance. A companion paper [16••] developed a bounded General Least Squares (bGLS) method for parameter estimation by reformulating the linear phase correction model in terms of matrix algebra (see Box 1).

## Correcting for a shift of phase in the metronome

So far, the phase correction model has been discussed in the context of corrections arising from the participant's own timing errors with respect to a fixed interval (or isochronous) metronome. However, it is also interesting to consider the complementary case when a timing error is introduced by the metronome. When just one of the metronome intervals is lengthened or shortened, shifting the phase of all subsequent pulses, participants must adjust their timing to regain synchrony with the beat (see Figure 1b). This corrective response can be used to give a direct measure of the correction gain in terms of the proportional reduction in asynchrony on the response following the phase shift event. Interestingly, the same correction occurs regardless of effector, be it upper limb (e.g. finger tapping, [17]) or lower limb (e.g. stepping, [18]). However, the correction gain immediately following a perturbation is much larger than the gain estimated from steady state series [19], suggesting a different correction mechanism may come into play for sudden perturbations to the metronome phase.

**Box topic 1 The bGLS method**

The bGLS method uses the inter-stimulus intervals (i.e. the intervals between cue onsets; $S_n$) and the asynchronies between the participant's movement onset and the cue onset ($A_n$) to estimate the linear phase correction parameters (motor variability, $\sigma_M$, timekeeper variability, $\sigma_T$, and correction gain, $\alpha$). The component intervals (see Eq. (1)) are arranged in matrix format as follows (from [16•]):

$$y = Bx + Z$$

where $y = [A_1 + S_1 - E(A+S), A_2 + S_2 - E(A+S), \ldots, A_n + S_n - E(A+S)]^T$; $B = [A_0 - E(A), A_1 - E(A), \ldots, A_{n-1} - E(A)]^T$; $x = 1 - \alpha$; $Z = [H_0, H_1, \ldots, H_{n-1}]$; and $H_n = T_n + M_{n+1} - M_n - E(T)$

$E()$ represents the mean value across the time series.

$Z$ is considered as multivariate Gaussian noise, with the covariance matrix defined as:

$$\Sigma = Cov(Z) = \begin{bmatrix} \gamma(0) & \gamma(1) & 0 & 0 \\ \gamma(1) & \ddots & \ddots & 0 \\ 0 & \ddots & \ddots & \gamma(1) \\ 0 & 0 & \gamma(1) & \gamma(0) \end{bmatrix}$$

If $\Sigma$ was known, then the estimate of $x$ could be achieved using the General Least Squares approach:

$$x = \left(B^T \Sigma^{-1} B\right)^{-1} \left(B^T \Sigma^{-1}\right) y$$

Alternatively, if $x$ was known, then $\Sigma$ could be estimated by the lag 0 and lag 1 autocovariances of $y - Bx$

$$\Sigma = \gamma_0 I + \gamma_1 \Delta$$

where $I$ is the identity matrix and $\Delta$ is a matrix containing ones on the diagonals either side of the central diagonal and zeros elsewhere.

However, both $x$ and $\sum$ are unknown values to be estimated. The estimates are therefore achieved by an iterative approach, first estimating $x$ by setting $\Sigma = I$. Using the first estimate of $x$, an updated estimate of $\Sigma$ is calculated, and so on, until the $x$ and $\Sigma$ values converge to a stable value. The constraint defined in Jacoby *et al.* [15], means an additional step is added to the iteration, that checks the autocovariance values meet the condition:

$$0 < -\gamma_n(1) < \gamma_n(0) + 2\gamma_n(1)$$

If not, an adjustment is made to $\gamma_n(1)$, to ensure the constraint is met before the next iteration is executed.

The bGLS method has been shown to be a flexible method that allows parameter estimation under a number of different conditions such as phase and period-shifted metronomes (see Section '*Correcting for a shift of phase in the metronome*', [19]), ensemble timing (see Section '*Multi-person synchronisation*', [16•]) and ensemble bimanual timing (see Section '*Multi-person synchronisation*', [32]).

Correcting for a phase shift requires a change in the target tapping interval until synchrony is regained. The question which arises is whether this adjustment to the tapping interval involves a change in the period of the central timekeeper? A variant of the phase shift task addressed this question, whereby the metronome was switched off immediately after the phase shift and participants were instructed to continue tapping at the same pace [20]. The period change observed in the subsequent finger tap intervals suggested that phase correction resulted in an adjustment to the central timekeeper interval. Differences in the involvement of period change in the phase shift paradigm and the constant metronome paradigm might in part account for the correction gain differences observed in [19].

## Tempo tracking

Changes in tempo are sometimes encountered in periodic timing tasks. For example, musicians often vary their timing by speeding up or slowing down as an expressive interpretation of a musical piece. It is therefore interesting to consider the results of finger tapping studies which called for tempo changes to examine underlying timing control mechanisms. Schulze *et al.* [21] studied transitions between pairs of target metronome intervals selected from 300, 370, 440, and 510 ms. Each trial began with between 17 and 22 intervals at the base duration before the metronome transited with a sigmoidal trajectory towards the new interval duration. Asynchrony data from five participants showed systematic departures from the metronome in the form of two cycles of getting behind (when the metronome was speeding up) or ahead (metronome slowing down) of the beat. The lag or lead response to the transition resulted in positive (upward) or negative (downward) signed asynchronies, thus producing a characteristic M or W pattern of deviations from the initial baseline asynchrony. A model based on phase correction, as in Eq. (1), combined with correction of the timekeeper period in proportion to the preceding asynchrony, was used to fit the observed asynchrony time series using numerical minimisation. The model provided reasonable qualitative fits to the asynchrony data during tempo change, and performed better than an alternative model which was based on adjusting the timekeeper according to a weighted average of previous timekeeper and metronome intervals [22,23]. However, different parameters were required to account for the asynchrony time series in the steady state before and after tempo change, suggesting the need to turn the timekeeper period correction on and off as an ad hoc component of the model.

In Schulze *et al.* [21] the tempo changes varied from trial to trial, and so were unpredictable. However, where tempo changes are predictable (perhaps because of a blocked design or through rehearsal), performers might adjust their timing in anticipation of further change in tempo rather than wait and react to increasing asynchrony after tempo change is first detected. Van der Steen *et al.* [24•] studied finger tapping to a 400 ms metronome which went through a number of cycles of tempo slowing down (to 600 ms) and speeding up (back to 400 ms) with rates of tempo change varying (in separate blocks of trials) at up to 14, 28, or 44 ms for each successive interval (with 1, 2, and 3 slowing-speeding cycles respectively). The results showed that the standard deviation of asynchrony increased with number of cycles (tempo change rate). Using the bGLS method ([16••], see Box 1) to estimate phase and period correction, as defined in [21], phase correction increased and period correction decreased with rate of change of tempo. Cross-correlations between the metronome intervals and IRIs, which were strongly positive at lag zero and somewhat lower at lag one, decreased with tempo change rate. This pattern suggests a stronger tendency to anticipate (lag zero) than to match the previous (lag one) metronome interval, with less anticipation at faster tempo change rates.

The correlation results mentioned above indicate the contribution of an anticipation process. Therefore, it is interesting to consider extensions to the phase and period correction model [21] by combining anticipatory and adaptation components. Three such models based on an earlier simulation study [25] were explored in [24•]. In the first model, the next response was determined as the weighted sum of the previous interval and the predicted next interval (based on linear extrapolation of the previous two intervals) plus a phase correction term (as Eq. (1)). In the second and third models, there was, again, a combination of anticipation and adaptation components (with the minor difference of phase versus period correction in the two models) but this was used as input to produce an internal prediction of the expected asynchrony. Feedforward correction was then used to reduce the asynchrony when the response was made. The parameters of these models were estimated using the bGLS method [16••] which also provided goodness of fit measures. In comparison with a model using only basic adaptation, the three models with anticipation provided reliably better fits to the data and, in the case of the two higher tempo change rates, the two models which incorporated feed-forward correction out-performed the one that did not. In conclusion, the results suggest the importance of including anticipatory components in future work in this area.

## 2-person synchronisation

We now turn to consider 2-person synchronisation with an example from music. In a study reported by Goebl and Palmer [26], pairs of participants, wearing headphones to control auditory feedback, played upper and lower parts of a simple duet at 133 bpm on a MIDI piano. When players were able to hear each other, cross-correlation functions showed that the intervals between tone onsets were positively correlated at lags plus and minus one (an interval of one player was related to the previous and following interval of the other), and negatively correlated at lag zero (concurrent intervals of the players were inversely related). However, when listening was restricted so that only one player heard the other, the lag one cross-correlation was limited to dependence of the hearing player on the other. Similar results were obtained for finger tapping in [27]. These results suggest that, in normal 2-person synchronisation, each participant uses feedback from the other (bidirectional correction) to correct the current interval for mismatch of the previous interval or asynchrony in the preceding note onsets.

A formal model of 2-person synchronisation was developed by Vorberg [28••] for the situation in which participants synchronised with a computerised metronome. The metronome software was programmed to synchronise the beat onsets with the participant's own tapping responses using the first order linear phase correction model (Eq. (1)). This effectively simulated the correction responses of a virtual human participant tapping in time with the real participant. At the same time, the real participant was correcting his or her own responses to those of the virtual participant. The authors manipulated the correction responses of the virtual participant by varying the correction gain. They estimated the correction gains of the human participants to the virtual partner by fitting the linear phase correction model (Eq. (1)) to their tapping data. Additional manipulations were subsequently investigated by Repp and Keller [29••]. Given the two correction gains, $\alpha_S$, for the simulated responses and $\alpha_H$, for the measured gains of the human participant, Vorberg showed that for correction between the human and virtual partner to remain stable, the sum of the gains must be between zero and two (i.e. $0 \leq (\alpha_S + \alpha_H) \leq 2$) [28••]. It should be noted that this stable range is the same as that for a single person synchronising with a fixed metronome (see Section '*Synchronisation with a fixed metronome*' and Figure 1b), suggesting that regardless of the number of people synchronising, the sum of the correction gains must remain within this range to achieve stable synchrony. This was further corroborated by Wing *et al.* [30•] who investigated timing corrections between string quartet musicians (see Section '*Multi-person synchronisation*').

A synchronisation model corresponding to that of Vorberg's [28••] was also explored by Hayashi and Kondo [31]. They instructed six pairs of performers (pairings made up from four individual participants) to tap together at different frequencies ranging from .5 to 1 Hz. While tapping, participants saw a visual flash representing each tap of their partner. Using regression to estimate correction gain, they observed decreases in the sum of the pairs' correction gains with increasing frequency. They further found that the gain values differed for the two members of each pair. The authors suggested this could be seen as a division of roles (a smaller gain being consistent with being more of a leader). However, they also noted that there was no consistency across pairings, with gains for a certain individual fluctuating depending on partner. Therefore, leadership might be said to be defined relative to each partner rather than in absolute terms.

## Multi-person synchronisation

An early study into group timing was undertaken by Wing and Woodburn [1] who used rowing eights to investigate between rower timing corrections. In a racing eight, oars along the boat alternate to the left and right. Successful rowers must attempt to maintain the same tempo with synchronous catches as the oars enter the water at the start of each stroke. It is particularly important that oars on the same side should maintain their physical separation so as not to make contact with each other. This led the authors to hypothesise that between-oar timing corrections, measured using inter-catch interval cross-correlations, should be stronger between pairs of oars on the same side, than for oars on opposite sides of the boat. However, the cross-correlation functions failed to conform to this prediction, suggesting that oars on the two sides of the boat use a common timing cue to maintain synchrony, such as the acceleration–deceleration cycle of the boat motion (or associated sounds) during rowing.

Using chamber quartets as their study group, Wing *et al.* [30•] extended the linear phase correction model to allow pairwise analysis of synchrony between members of the quartets (Eq. (2)).

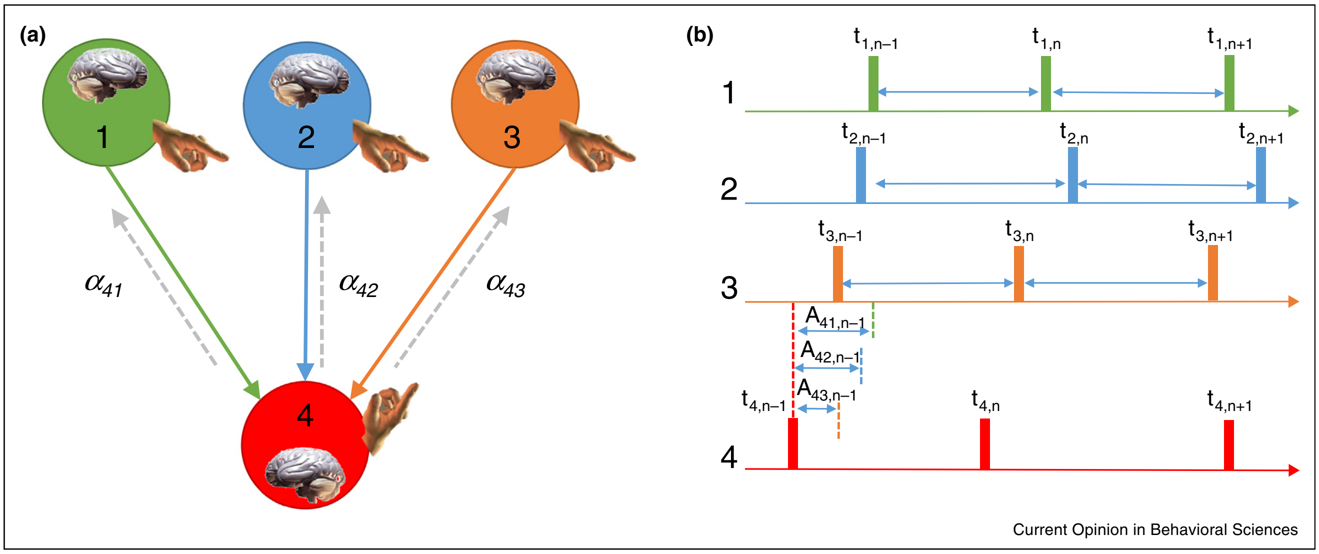
$$t_{i,n} = t_{i,n-1} + T_{i,n-1} - \sum\nolimits_{j=1,j\neq 1}^{4} \alpha_{ij}(t_{i,n-1} - t_{j,n-1}) + \varepsilon_{i,n} \qquad i = 1,\ldots,4 \qquad (2)$$

where $t_{i,n}$ and $t_{i,n-1}$ are current and previous observed tone onset event times for Player $i$, $T_{i,n-1}$ represents the timekeeper interval, $\alpha_{ij}$ refers to the correction gain applied by Player $i$ for the asynchrony $(t_{i,n-1} - t_{j,n-1})$ with Player $j$ and $\varepsilon_{i,n}$ is a random noise term identified with the assumed internal timekeeper (see Figure 2).

What values of correction gain would be appropriate for four performers playing in an ensemble? For stable performance when tapping with an adaptive metronome ('duet performance'), the sum of gains should be bounded between 0 and 2 [28••; see Section '*2-person synchronisation*']. Wing *et al.* [30•] further showed that the condition for stable synchronisation, stated as the sum of the two correction gains in the dyadic studies [28••] extends to larger groups, $N > 2$. They showed that stability of the linear phase correction model of ensemble timing requires each player to maintain a correction gain of between 0 and $2/N$, assuming all gains are equal. More specifically, the authors showed that a gain of $1/N$ minimises asynchrony variance, that is to say, as group size increases, the optimal gain for each member decreases. They also showed that the form of the AACF is over-damped, critically damped or under-damped when gain is respectively less than, equal to or greater than $1/N$.

An empirical study in support of the first-order linear phase correction model embodied in Eq. (2) was included in [30•]. Two professional string quartets were asked to play a 48-note excerpt from Haydn's Quartet Op. 74 No. 1 fifteen times, with individual players encouraged to introduce unrehearsed, different intentional timing variations on

**Figure 2**



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**(a)** Extended model for multi-person timing based on Wing *et al.* [30•]. Rather than a single cue, there are now $N$ simultaneous cues for each ‘event’. In the figure we show an example for $N = 4$, and focus on participant 4, who is synchronising with the movements of the remaining group members, 1, 2, and 3. The reliance on each of the members is reflected in the correction gains, $\alpha$. The dashed grey lines highlight that correction is bidirectional between all members. **(b)**. The next movement onset is now based on the sum of the asynchronies between group member 4 and the other group members, weighted by individual correction gains, $\alpha$. Note that the Wing *et al.* model does not explicitly separate motor and timekeeper variances, and instead groups this under a single noise term. The model has been subsequently extended to a full multi-person two-level timing model by Jacoby and colleagues in [16].

each trial. The asynchronies between players in each of the quartets were used to estimate correction gains within the phase correction model using an iterative least squares procedure to fit the observed asynchrony time series. The results revealed a stable set of between-player gain estimates. The overall average gain for quartet A was 0.19, and 0.23 for quartet B. However, it was expected that the gain profiles would differ between players, reflecting the lead traditionally taken by the first violinist. Wing *et al.* found this to be true for quartet A. The gain for Violin 1 was consistently lower than other players indicating that Violin 2, Viola, and Cello adjusted more to Violin 1 than vice versa. In contrast, all players in quartet B had similar gain values, suggesting that all players corrected more or less equally to each other.

This music study revealed two contrasting patterns of gain, with one quartet showing asymmetries in correction gains (the leader employed reduced gains), whereas in the other quartet the gains were symmetric (more or less equal between all players). The spatial arrangement of a quartet affords both visual and auditory cues between players so equality of gains is perhaps to be expected by default, with Quartet B playing in a more democratic, leader-less style. In contrast, Quartet A appeared to adopt the traditional approach of Violin 1 taking a lead role.

Honisch *et al.* [32] used explicit leader-follower relationships to investigate correction gains in a synchronisation task involving passing of visual timing cues along two separate ‘chains’. The task in [32] required six individuals, seated facing outward in a circle, to move their left and right arms up and down together at a rate set by a metronome which only one person, designated the Leader, could hear. Two pairs of Followers on either side of the Leader formed chains whose timing was linked to the Leader’s left and right hands. In each chain Follower-1 (F1) was required to watch the hand of the Leader, while Follower-2 (F2) watched the hand of F1 to pick up the tempo. This arrangement was intended to encourage the passing of timing cues from the Leader around the circumference of the circle in a way that would be reflected in the correction gains. Larger correction gains were expected for the Follower relative to the target hand providing the timing cue on the side nearer the Leader than the correction gain computed with respect to any other participant. To complete the circle, an individual designated the Integrator, sat between the ends of the two chains and observed movements from the two participants on their left and right sides. A primary finding was that participants in the Leader and Follower positions used a strategy of minimising their asynchrony variance whereas, in the Integrator position, participants switched to a strategy that minimised their own movement variability. However, from the point of the present review, particularly interesting was the finding of an asymmetry in the correction gains that reflected access to visual information. Thus Leader-F1 and F1 — F2 gains were consistently larger than gains estimated with respect to all other pairings of group members. Thus, correction gain was influenced by the spatial constraints of the task.

## Conclusions

In summary, we have reviewed how event-based linear models for a single performer tapping with a fixed metronome can generalise into testable accounts of interpersonal timing. We have taken a linear systems approach in which behaviour, and underlying generative mechanisms, are treated as stable over time. However, instability over repetition is often observed in cyclic movement tasks. Non-linear dynamical systems approaches to timing focus specifically on such instabilities and there is a growing body of work taking this perspective focused on two-person timing interactions (for review see Schmidt and Richardson [33]). Within the linear approach described here, a number of further questions might be explored in future research, some of which we highlight here. In the above, we have not examined mean asynchrony, but it is interesting to ask, for instance, whether mean asynchrony of the leader in a group increases with group asynchrony variance, which would be useful in aiding a listener to detect the timing lead. In thinking about asynchrony variance, it is pertinent to investigate if variance reduction, for example with practice, is more determined by sensory (listening), cognitive (timekeeper), or motor constraints. More specifically, are reductions in asynchrony variance related to familiarity between players or to the musical material being performed? We might also consider if correction gain values are consciously adjusted higher or lower by the group to influence the players' (or listeners') experience of group timing.

We note one further potential area for research and that involves brain mechanisms underlying synchronisation processes. For example, group timing effects on brain activation might be investigated in neuroimaging studies following seminal work by Keller and colleagues on brain activations when synchronising with an adaptive metronome [34,35•]. Taking all these questions together, we therefore feel confident in claiming that here is a fertile area for quantitative models of social interaction [see Box 2] in areas of activity that impact on many aspects of cultural life and, as such, this is an area which merits further research blending empirical study with theoretical tools of the kind described in this review.

**Box topic 2 Social implications of multi-person timing**

The process of achieving and maintaining synchrony is arguably a social experience. It is an intentional act of temporally aligning one's actions with one or more interacting persons to attain a shared goal. Beyond the physical success of coordination expected in activities such as rowing or ensemble music, does such interaction also produce an impact on other non-temporal aspects of behaviour?

Indeed, engaging in synchronous behaviour has been shown to lead to an increased prospect of liking a person [36], identification with group membership [37], perceived similarity [38], and self-other overlap [39]. As a result, prosocial behavioural outcomes such as better cooperation [40] and altruistic actions [38] have been observed. Interestingly, the positive effects of synchrony are not unique to adults. At 8 or 9 years old, children who had been finger tapping together for only three minutes expressed more similarity and closeness to their tapping partner when their task partner tapped in synchrony with them [41]. At an even younger age of 14 months, infants were more likely to help an experimenter pick up a dropped object if they had been passively bounced in synchrony with the experimenter prior to the task [42]. Imaging studies have started to draw the link between synchrony and social affiliation by looking at areas of the brain involved in a synchrony task. The same areas recruited for the task have also been implicated in social cognition and embodied cognition, providing neural evidence of the social consequences of synchrony [43].

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## Conflict of interest statement

Nothing declared.

## References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

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