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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 feed-forward 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 nth 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, σ_T^2, that determine synchronisation accuracy with the metronome. Timekeeper variability tends to increase with longer interval durations, whereas motor variability, σ_M^2, remains at a relatively small value [7–9].

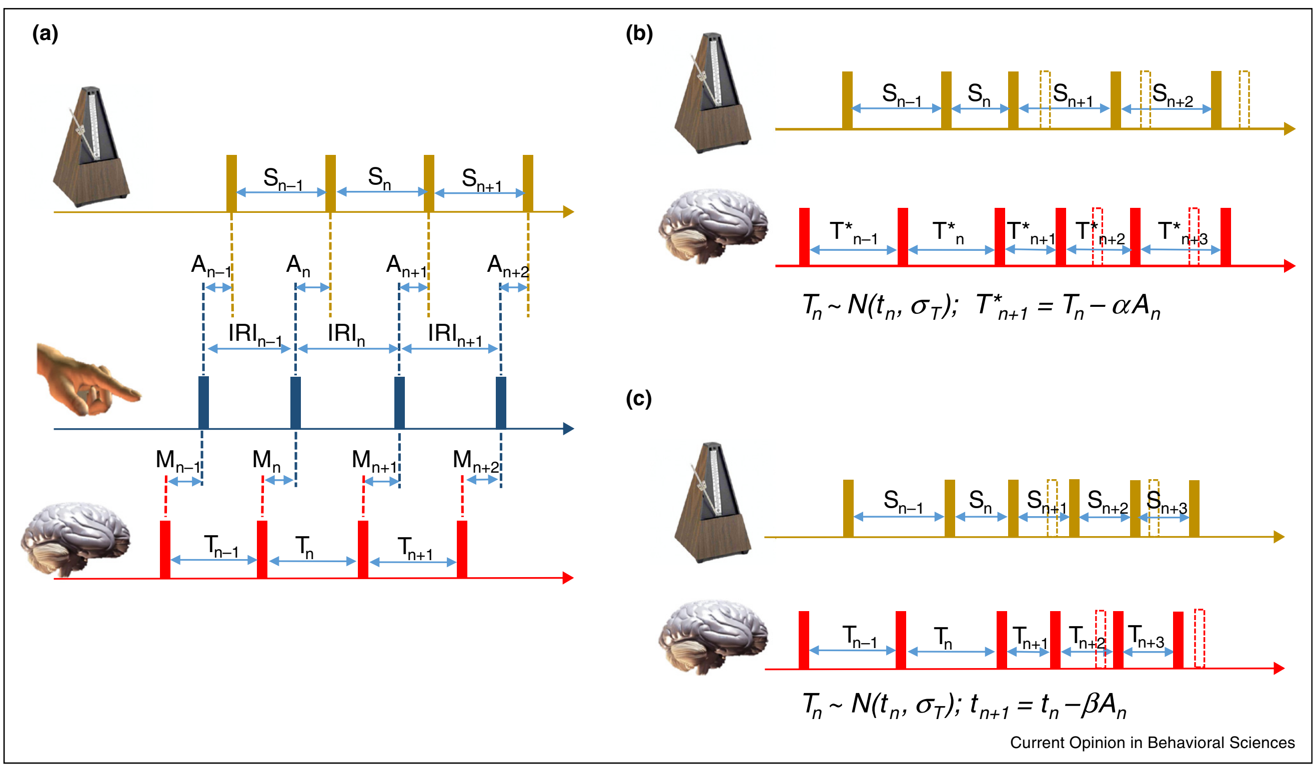
The ability to synchronise with a metronome (for reviews see [10,11•]) despite the presence of variability in timed periodic movement, implies feedback correction. Vorberg and colleagues proposed a first-order linear phase correction model, in which the asynchrony between the finger tap and related metronome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

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

where α 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, α, 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, σ_T. The amount of correction is based on the last asynchrony (A_{n-1}) multiplied by a correction gain, alpha (α). 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*, β, 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.