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Getting synchronized with the metronome: Comparisons between phase and period correction

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Abstract Most studies of synchronization have focused on how an established phase relationship between self-produced events (e.g., finger taps) and the clicks of a metronome is maintained when the metronome is regular or subject to unpredictable perturbations. Here we study how synchronization is initially established, using an experimental paradigm in which the metronome is activated after the subject has executed a series of self-paced finger taps. In Exp. 1, the metronome period was constant and equal to the mean of the self-paced inter-response intervals, whereas the initial phase difference of the metronome from the taps varied across trials. The synchronization error patterns could be predicted by a linear phase correction model. Experiment 2 involved both period and phase correction. The initial phase difference was constant, whereas the metronome period varied across trials. The observed synchronization error patterns suggest that the subjects achieved synchronization either by reacting to the second metronome signal or by aiming at the third metronome signal. The pattern of the residual synchronization errors was consistent with the linear phase correction model. These results support the notion that period and phase correction mechanisms are called for by different task variables and contribute differently to sensorimotor synchronization.

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Introduction

Sensorimotor synchronization involves motor acts (e.g., finger taps on a response key) which are generated in such a way that each of them coincides with an individual stimulus within a sequence. In the easiest version of the task, the stimuli are evenly paced and follow each other at a fixed inter-stimulus interval like the isochronous clicks of a metronome. Successful performance in this task requires a process which generates the motor events at predetermined points in time (timekeeper mechanism) and another process which monitors how close in time the motor events come to their corresponding stimuli (sensory control mechanism). Timekeeping must be assumed because human subjects can synchronize to stimulus sequences at quite different tempos, producing taps which lie close to, but typically slightly ahead of the stimulus events. This negative phase error excludes any interpretation of synchronization in terms of the subject reacting, as fast as possible, to the successive stimuli (for a review, see Aschersleben, 1994). Sensory control must be assumed because human subjects can maintain synchronization even with a metronome that produces randomly varying intervals (Schulze, 1992) and in spite of the fact that timekeeper mechanisms, like any biological system, are prone to random variability.

Since synchronization requires timekeeping and sensory control, synchronization tasks have become popular in the experimental study of time perception and temporal organization of behavior (e.g., Aschersleben, 1994; Bartlett & Bartlett, 1959; Dunlap, 1910; Fraisse, 1956; Kolers & Brewster, 1985; Vos, Mates, & van Kruysbergen, 1995; Woodrow, 1932). Modeling sensorimotor synchronization has a shorter history (Michon, 1967; Voillaume, 1971) but there is a recent rise in theoretical interest (Hary & Moore, 1987; Schulze, 1992; Vos & Helsper, 1992; Mates, 1994a, b; Vorberg & Wing, 1994, 1996). All these models agree with the notion that the coupling between the sequence of stimulus events and motor events involves some form of closed-loop sensory feedback mechanism.

One such mechanism is supposed to adjust for *phase errors* between stimulus and response events, taking the phase error (or *asynchrony*) between the last response and stimulus events as input, and correcting the next internal timekeeper interval by increasing or decreasing it by some fraction of that error. The amount of correction depends on the value of a gain parameter (see Hary & Moore 1987; Mates, 1994a, b; Schulze 1992; Vorberg & Wing, 1996). Phase errors are typically due to random variability in the timekeeper mechanism, if not deliberately introduced by the experimenter by using a metronome with small random fluctuations around a constant period mean. Another strategy is to correct for discrepancies between the timekeeper period mean and the metronome period. It has been suggested that such a mechanism takes the *period error* (i.e., the difference between the timekeeper interval and the last inter-stimulus interval) as input, and modifies the target interval of the timekeeper accordingly (see Mates, 1994a, b; Michon, 1967; Vos and Helsper, 1992).

The synchronization models that have been proposed differ in the relative importance they give to period correction and phase correction processes, respectively. For instance, Michon's (1967) pioneering work on sensorimotor synchronization mainly concentrated on period correction, which reflects his approach of describing performance in terms of the human operator's transfer function, best studied via synchronization to stimulus sequences with step, sinusoidal, or random tempo variation. In contrast, the model put forward by Vorberg and Wing (1996) focuses on phase correction because phase correction strategies seem sufficient for maintaining synchrony with a metronome that has a stable mean tempo and because the resulting stochastic model admits deriving explicit predictions that can be tested empirically.

Despite different emphasis on phase versus period correction, all models predict asymptotic stationarity of the synchronization errors under appropriate conditions. The steady-state asynchronies between stimuli and responses provide the data base for studies of the limits of synchronization to sensory stimuli and for studies that test formal models of synchronization. Another approach is to study how synchronization performance becomes stationary again after an experimental perturbation of the phase or period relationship. This approach typically involves comparing data and theoretical predictions about the statistics of the inter-stimulus and the inter-response intervals (see Hary & Moore 1987; Mates, 1994a, b; Michon, 1967; Vos & Helsper, 1992).

In the present study, we focus on how the inter-response intervals and asynchronies evolve during the *initial*, non-stationary stage of synchronization and describe their trajectories in terms of a model. Two experiments will be reported. The first experiment required adjusting the timekeeper phase only. We examine whether the asynchrony trajectories follow the predictions of the two-level timing model for synchronization proposed by Vorberg and Wing (1996). The second experiment required adjusting both timekeeper phase and period. We analyze which strategies subjects use when they try to establish synchrony with a metronome whose tempo differs from their own tempo.

The paper is organized as follows. First, an extension of the two-level timing model for synchronized tapping will be presented. Then we report the two experimental studies. Finally, we discuss some general problems pertinent to phase and period correction and suggest directions for future research.

The two-level timing model for synchronization

The two-level timing model for synchronization, proposed by Vorberg and Wing (1996), adopts the architecture of Wing and Kristofferson's (1973) two-level timing model for self-paced isochronous tapping. The latter model assumes that the temporal precision in tapping is jointly determined by the accuracy of an internal timekeeper and by the variability that arises when the central commands are executed by the peripheral motor system. According to the model, each observable inter-response interval in a sequence of overt motor acts (e.g., finger-taps on a response key) is determined by a timekeeper interval and by the delays that intervene between the central commands and the overt motor responses which initiate and terminate the inter-response interval (for details, see Wing & Kristofferson, 1973; Wing, 1980; Vorberg & Wing, 1996).

Vorberg and Wing (1996) have examined extensions of this two-level model to synchronization with a metronome, and supplemented the two-level architecture with a linear feedback mechanism that adjusts for phase differences. As in the original model, the inter-response intervals can be expressed as a linear combination of internally generated intervals and motor delay components:

$$\mathrm{I}_n = \mathrm{T}_n^* + \mathrm{M}_{n+1} - \mathrm{M}_n \tag{1}$$

The central component T_n^* consists of a timekeeper interval plus a correction term. A crucial assumption is that the timekeeper mean approximates the metronome period and need not be adjusted. The subject is assumed to correct only phase differences between metronome clicks and taps, locally adjusting each timekeeper interval T_n by subtracting a fixed proportion of the last synchronization error A_n:

$$\mathrm{T}_n^* = \mathrm{T}_n - \alpha \mathrm{A}_n \tag{2}$$

Note that the timekeeper period, $\mathrm{E}(\mathrm{T}_n)$, remains unaffected by the adjustment.

Vorberg and Wing (1996) have analyzed the dynamic properties of this model and derived predictions about the variability and dependence structure of the asynchrony and inter-response interval sequences in synchronization. They showed that the phase-correction scheme leads to synchronization performance that is asymptotically stable in the means, variances, and covariances even if the mean timekeeper period is biased, i.e., differs from that of the external metronome. In this paper, we will use the model as a tool for studying the initial, transient stage in synchronization; we focus on the asynchrony and inter-response interval means. Tests of the model's ability to account for their variability and dependence structure as well will be presented elsewhere (Semjen, Schulze, & Vorberg, 1997).

We surmised that the original Vorberg and Wing (V & W) model which was proposed for synchronization performance in the stationary state might be limited in accounting for the initial stage of synchronization in two ways:

(a) From the linear first-order phase-adjustment assumptions (Eq. 2), the asynchrony mean is predicted to approach the asymptote in a geometric fashion, which need not hold under all experimental conditions.
(b) A strong prediction of the model is that the mean synchronization error vanishes asymptotically if the metronome period equals the timekeeper mean. One of the aims of Exp. 1 was to test this prediction.

For these reasons, we based our data analysis on an extension of the V & W model (for a detailed analysis, see Vorberg & Schulze, 1997). The extended model admits second-order phase-adjustment; moreover, it assumes that phase adjustment is based on the subjective, perceived asynchronies rather than on the objective, physical asynchronies, that is, on the synchronization errors that are registered internally after some perceptual delays. In the extended model, Eq. 2 is thus replaced by

$$T_n^* = T_n - \alpha S_n - \beta S_{n-1}$$

It is assumed that the n-th metronome click is registered with delay $P_{M,n}$, and, analogously, the n-th response with delay $P_{R,n}$, which implies that the internal asynchronies, S_n, are related to the overt asynchronies, A_n, by

$$S_n = A_n + P_{R,n} - P_{M,n}$$

Writing D_n for the difference $P_{R,n} - P_{M,n}$ between the perceptual delays leads to the modified phase-adjustment equation

$$T_n^* = T_n - \alpha(A_n + D_n) - \beta(A_{n-1} + D_{n-1}) \tag{2*}$$

Equations 1 and 2*, together with the definition of the asynchronies in terms of the metronome and the inter-response intervals, imply that the successive asynchronies are governed by the stochastic difference equation:

$$\begin{aligned} A_{n+1} = (1-\alpha)A_n - \beta A_{n-1} + (T_n + M_{n+1} - M_n) \\ - \pi - (\alpha D_n - \beta D_{n-1}) \end{aligned} \tag{3}$$

whereby π denotes the metronome period.

In the extended model, the asynchronies as well as the timekeeper, motor delay, and perceptual delay differences are random variables. Taking expectations on both sides of Eq. 3 gives

$$\begin{aligned} E(A_{n+1}) = (1-\alpha)E(A_n) - \beta E(A_{n-1}) \\ + (\mu_T - \pi) - (\alpha + \beta)\mu_D \end{aligned} \tag{4}$$

which shows how the mean synchronization error of the $(n+1)$-th tap depends on the two preceding synchronization errors, the deviation of the mean timekeeper interval from the metronome period, $\mu_T - \pi$, and the mean perceptual delay difference, $\mu_D = E(P_{R,n}) - E(P_{M,n})$. Note that the trajectory of the asynchrony means follows a deterministic law, and that, contrary to the predictions for the variances and covariances (see Vorberg & Schulze, 1997), the contribution of motor delays vanishes because $E(M_{n+1}) = E(M_n)$.

Equation 4 can be used to predict what happens when a metronome that perfectly matches the subject's timekeeper comes in with some phase delay. The initial asynchrony determines the trajectories of the asynchronies and inter-response intervals that follow. It can be shown that if the initial synchronization error exceeds the asymptotic error, the subject is predicted to achieve synchronization by producing inter-response intervals (IRIs) that are *shorter* than the metronome period, whereas if the initial synchronization error is smaller, synchronization will be achieved by IRIs that are *longer* than the metronome period.

Experiment 1

The aim of this experiment was to study the asynchrony trajectories in the transient part of synchronization and to compare them to the trajectories predicted by the model. We systematically varied the phase difference between the metronome and the subjects' responses and examined its effects on subsequent synchronization.

Our experiment reversed the synchronization and continuation phases of the standard tapping paradigm; self-paced tapping preceded synchronized tapping. A trial began with the subject tapping evenly at his/her preferred rate. After a fixed series of self-paced taps, the metronome came on with a period that was equal to the mean of the IRIs in the self-paced episode. Subjects were informed about the onset of the metronome at some time. They knew that the metronome maintained their pace but had an unpredictable phase difference. Their task was to achieve synchronization smoothly.

By setting the metronome rate equal to the self-selected timekeeper rate, we tried to shed light on the question why, in the steady-state, an anticipation bias is observed in most studies, that is, why taps tend to lead the metronome events (for a review, see Aschersleben, 1994). In spite of much recent experimental and theoretical work, the answer to this question is still controversial.

Many authors have noted that synchronous physical events (e.g., a finger contact on the response key and a click of the metronome) may lead to asynchronous central representations, which is the case if the nerve conduction times, sensory thresholds, or perceptual centers related to those events differ (Aschersleben, 1994; Gehrke, Aschersleben, and Prinz, 1997; Vos, Mates, and van Kruysbergen, 1995). Perceived simultaneity may require non-simultaneous physical events, and the anticipation bias might thus be a measure of the difference in their internal delays. It has been pointed out, however, that anticipation bias also follows from optimal phase-correction strategies (Vorberg & Wing, 1996; Vorberg & Schulze, 1997). As in statistical estimation, where efficiency can often be improved by admitting estimator bias, linear phase-correction may lead to least squared-error synchronization if the timekeeper mean slightly undershoots the metronome period. In fact, anticipation bias is predicted by the V & W synchronization model whenever parameter values are chosen such that the expected squared synchronization error is minimal asymptotically, assuming that the variance of timekeeper increases with its mean.

These different theoretical accounts of the anticipation bias do not exclude each other. This implies that, in general, the observed anticipation mean potentially confounds the effects of perceptual delays with that of systematic timekeeper deviation from the metronome interval. This can be seen by taking the limit in Eq. 4 above. For appropriately chosen gain-factors α and β, the asynchrony mean tends to $E(A) = (\mu_T - \pi)/(\alpha + \beta) - \mu_D$, where μ_D denotes the mean difference in the perceptual delays. Obviously, the confound disappears if $\mu_T = \pi$, which means that experimentally setting the metronome rate equal to the timekeeper rate provides a simple test of the perceptual delay account. Unless synchronization involves period-correction, the timekeeper mean cannot change from its value during self-paced tapping. The asymptotic asynchrony mean observed under these conditions gives us a direct measure of the size of the perceptual delay difference.

Method

Subjects. Four female and two male subjects, in the age range of 22–57, participated in the experiment. The first author was one of the subjects. All subjects were right-handed and used their preferred hand when performing the tapping task.

Apparatus and measurements. The response key was a metal touch plate fixed to a table. The subject was seated with the forearm on the table and the index finger placed above the response key. The response key was interfaced to an Olivetti PC (M 290). Any onset and offset of contact between the finger and the response key was detected. IRIs, defined by successive contact onsets, were measured to the nearest millisecond. Via a sound card, the computer also controlled the presentation of the clicks which served as metronome signals. The clicks (1000-Hz square waves, 3-ms duration) were clearly perceptible; they were presented through loudspeakers placed above a video monitor, ca. 60 cm in front of the subject. The subjects could hear the sounds of their finger taps on the response plate.

At the beginning and the end of each trial, instructions and performance feedback were displayed on the video screen. Trials were interrupted when an IRI of less than 100 ms occurred, because they were probably due to bounce. Feedback was provided about the coefficient of variation (CV) of the IRIs during self-paced tapping; subjects were instructed to keep the CV as low as possible. Sequences with a CV exceeding 10% were discarded and the trial repeated.

Procedure. On each trial, the subjects started tapping after a message on the video screen went off; they produced 35 evenly paced taps at their preferred rate. The IRIs were monitored on-line and their mean was determined. The metronome was triggered by the 35th tap. Its period was equal to the mean IRI recorded in that trial, with phase delay equal to 5%, 35%, 65%, or 95% of the metronome period. Subjects were informed that the metronome would beat at their own tapping rate. They were requested to join the metronome as smoothly as possible, without interrupting tapping. The importance of precise synchronization was emphasized. The trial ended after 35 synchronized taps. For each subject a total of 64 correct trials were recorded, 16 for each phase delay. Within a block of 4 trials, the phase delays were presented once each, in random order. Each subject performed the experiment in a single session which lasted about 90 min.

Scoring the asynchronies. Because the metronome was triggered by the 35th self-paced tap, the first overt asynchrony occurred between this tap and the first metronome event (Fig. 1, top). This asynchrony is, by definition, negative (tap leading). If the synchronization model holds (see above), its correction should therefore involve a sequence of IRIs which are longer than the metronome period. In some circumstances, however, the subjective asynchrony that actually drives the phase-adjustment seems to have been the asynchrony between the first metronome event and the tap that follows it (see Fig. 1, bottom).

For instance, when the first metronome event is delayed by 65% or 95% of the IRI period, it is likely to occur much closer in time to the subsequent tap (tap 36) than to the tap that triggered the metronome (tap 35). For the subject, this temporal proximity could designate the asynchrony between the metronome event and the 36th tap as the error to be corrected for. Note that, in this case, the tap lagged the metronome event, and the correction of this positive asynchrony should lead to IRIs that are shorter than the metronome period. Therefore, we defined the first asynchrony either with respect to tap 35 or with respect to tap 36, depending on the trajectory of the subsequent IRIs.

Results and discussion

During self-paced tapping, subjects differed in their preferred tempo, as can be seen from the IRI means. The asynchronies, averaged over the last 25 synchronized taps, also revealed individual differences. Over all subjects, the asymptotic asynchronies did not differ with metronome phase, as the one-way ANOVA showed, $F(3, 15) = 1.58$, NS. More importantly, the asymptotic asynchrony was negative for each subject (see Table 1).

The asynchrony trajectory from initial to steady-state is shown in Fig. 2 for the different phase delay conditions. Dotted lines represent individual means; continuous thick lines represent the trajectories averaged over subjects. As expected, the initial asynchrony was small in the 5% condition (negative error) and in the 95%

Fig. 1 Possible definitions of the initial asynchronies (A_1, A_2...) between taps (*black arrows*) and metronome events (*white arrowheads*)

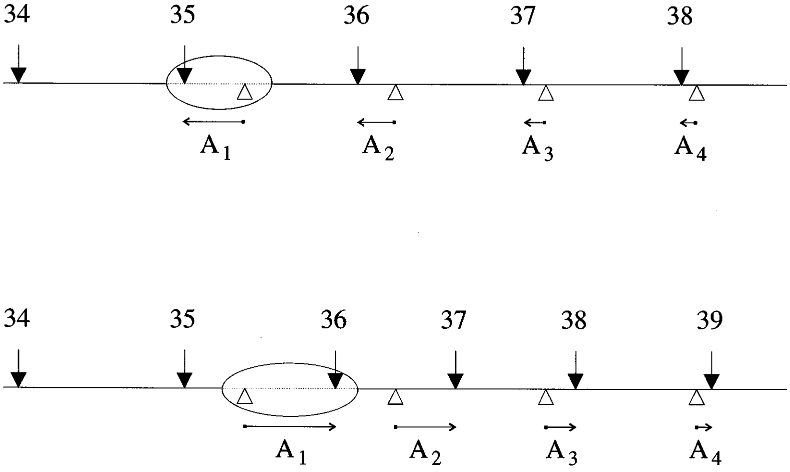


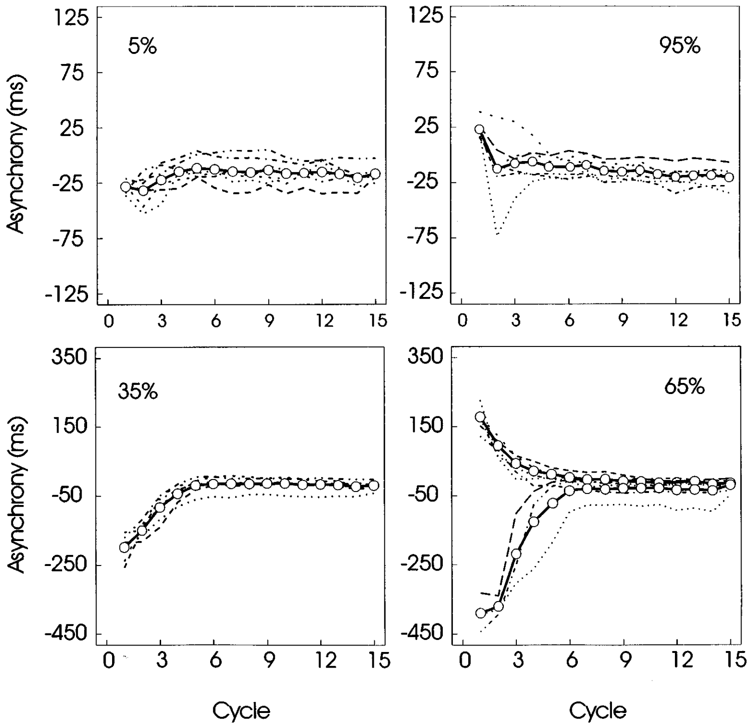
Table 1 Mean IRI (ms) during self-paced tapping and asymptotic mean synchronization error (ms)

Subject	IRI	Asynchrony
1	681.8	−13.25
2	534.3	−33.87
3	725.0	−25.90
4	535.3	−17.42
5	428.8	−19.20
6	486.3	−5.77
Mean	*565.3*	*−19.23*

condition (positive error). In the former case, the first asynchrony turned out to be very close to the steady-state level of asynchrony. In contrast, the 35% and 65% delay conditions induced large initial asynchronies. The asynchrony trajectories were generally consistent across subjects, except in the 65% initial phase delay case in which two types of trajectories could be identified from the sign (positive or negative) of the initial phase error. In this condition, three subjects seem to have considered the initial phase error as being positive in all trials, two subjects did so in the majority of trials, and one subject viewed the initial phase error as negative in all trials.

Mean asynchrony and IRI trajectories are shown in Fig. 3. The IRIs are expressed as deviations from the target interval, i.e., the metronome period. The initial points of the IRI curves represent the interval into which the first metronome event fell, that is, the IRI bounded by the 35th and 36th taps. For the 65% and 95%

Fig. 2 Mean asynchronies under each of the phase delay conditions (5%, 95%, 35%, 65%). *Dotted lines* = individual means; *continuous lines* (*circles*) = group means



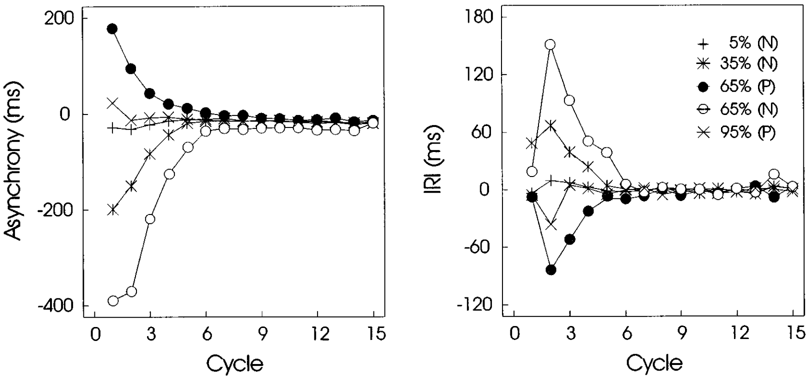


Fig. 3 Mean asynchronies and IRIs in the phase delay conditions. (*N*) = negative initial asynchrony. (*P*) = positive initial asynchrony

conditions, this IRI was close to the metronome period on average. For these delays, the subjects' behavior was most often guided by the asynchrony between the first metronome event and the tap closest to it, that is, the 36th tap, which *lagged* the metronome event. As can be seen in the graph (Fig. 3, right), this *positive* asynchrony triggered the phase correction process from the next response cycle onwards via a transient shortening of the IRIs. As already mentioned, in a few of the trials in the 65% condition, some subjects seem to have used the *negative* asynchrony between the 35th tap and the first metronome event but delayed phase correction: as evidenced by the unchanged first IRI, effective correction was triggered only from the next response cycle onwards, via a transient IRI lengthening.

When the metronome entered with a short delay (5% and 35% conditions), phase correction was achieved by transiently lengthening the IRI, which seems to indicate that the subjects' motor behavior was driven by the negative asynchrony between the tap and the subsequent metronome event. Note that under the 5% condition, the IRI initiated by the 35th tap was close to the metronome period, and the correction of the small phase error started only from the next response cycle on. In contrast, under the 35% delay condition, the very first negative asynchrony led to a correction, i.e., a lengthening of the current IRI. This correction was smaller than that in the next response cycle (cf. the lengthening of the IRIs in the first and second response cycles in Fig. 3, right). Altogether, these findings suggest that full efficiency of the phase correction process is not reached unless after a delay if there is temporal uncertainty about the onset of synchronization phase.

We fitted the synchronization model to these data by estimating the gain parameters, α and β, and the perceptual delay difference, μ_D. We determined the parameter values that minimized the sum of squared deviations of the predicted from the observed mean trajectories, separately for each subject. This analysis was restricted to the 35% and 65% phase delay conditions because the initial asynchrony in the two other delay conditions was either close to the steady-state value (5% condition) or sometimes led to erratic overcorrection (95% condition; see Fig. 2). Figure 4 shows the observed asynchrony means and the resulting predictions. The estimates are given in Table 2.

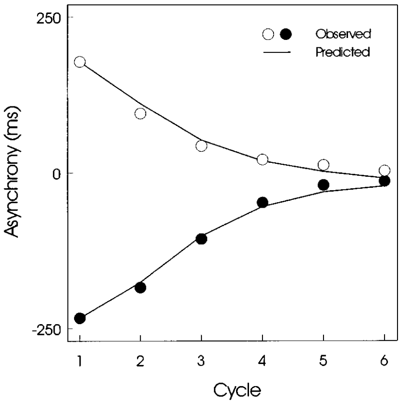


Fig. 4 *Symbols* = observed mean asynchronies; *lines* = mean asynchronies predicted from joint estimates of the model's parameters for the 35% and 65% phase delay conditions

A comparison of the observed and the predicted asynchrony trajectories shows that the extended two-level synchronization model describes the transition from self-paced tapping to synchronization quite well. The reader will have noticed that the two-level architecture of the model is not crucial for the prediction of the asynchrony and IRI means. More rigorous tests of the model must therefore include variability and sequential dependency predictions for the transient as well as the stationary parts of synchronization. An empirical evaluation of the model along these lines will be presented elsewhere (Semjen et al., 1997).

Table 2 Joint parameter estimates for the 35% and 65% phase delay conditions

Subject	α	β	μ_D	MSS
1	.18	.24	−12.1	191.4
2	.26	.03	−31.2	83.1
3	.58	.04	−24.5	70.1
4	.25	.15	−18.9	145.6
5	.20	.15	−14.3	169.7
6	.29	.16	−3.0	32.1
Mean	*.29*	*.13*	*−17.3*	*115.3*

On a more general level, our results indicate that motor organization in synchronized tapping depends on the phase relationship between response and metronome events, and that the asynchrony is the major determinant of the error correction process. This conclusion corroborates one of the central assumptions of the model. However, it is clear from the parameter estimates that a more realistic version of the model has to accept that it is not the physical but the subjective asynchrony on which the phase-correction scheme operates. Table 2 shows the parameter values obtained for the joint fit of the model to the data from 35% and 65% phase delay conditions. For all subjects, negative estimates of the perceptual delay difference, μ_D, were observed, with a mean of −17.3 ms. As was pointed out above, this value can be interpreted as an estimate of μ_D that is uncontaminated by timekeeper effects and has implications for the discussion why taps tend to lead rather than lag the metronome events. Clearly, (intentional or unintentional) timekeeper-metronome discrepancy is insufficient as the sole explanation of anticipation bias in synchronization.

A final comment on the effects of how subjects are to achieve synchronization is in order. Traditionally in synchronization studies, subjects are allowed to listen to the metronome sounds for several periods before starting to respond. Under this mode of synchronization, the phase error reaches stationarity within a few response cycles (e.g., Fraisse, 1966). Instructing our subjects to achieve synchronization smoothly without interrupting tapping produced different results. This instruction seems to compel subjects to attain stable synchronization overtly and gradually, as compared to experiments that permit covert preparation. Results from a recent study of ours shed additional light on the role of the instruction. In that study, subjects were asked *not* to synchronize but to maintain the initial synchronization error throughout the sequence. Contrary to the instruction, subjects could not prevent synchronization; on most trials, their taps progressively shifted towards the metronome. However, the asynchrony trajectories were different from those observed in the present experiment, showing either steady drifts or unstable coordination with the metronome.

Experiment 2

In Experiment 1 we examined how self-paced tapping is adjusted in phase to a metronome which beats at the same pace. The next step in our study of how synchronization is established was to examine how tapping is adjusted to a metronome which beats at a pace that differs from the taps. In other words, we want to know how period and phase correction are achieved concurrently. To this end, we modified our experimental task. As in the previous experiment, the metronome came in after a predetermined number of self-paced taps. This time, the metronome period was varied systematically, whereas the phase delay was kept constant. The subjects were informed that the metronome period could take on one of four different values but was constant within any one series. As before, the subjects were instructed to achieve synchronization smoothly.

In this situation where the metronome period is unpredictable, the timekeeper period cannot be updated before the second metronome event which provides the temporal information about the target period. Once this information is available, tapping can be adjusted to the metronome. There are alternative procedures by which the synchrony might be accomplished. For example, gradually accelerating or decelerating the tapping rate over a number of cycles will progressively reduce the discrepancy between taps and clicks. Alternatively, subjects might try to accomodate to the metronome period at a few discrete moments only and then follow such a global timekeeper change by a series of local phase adjustments. Conceivable strategies for discrete period adjustments are: reacting to the current metronome event or extrapolating the temporal position of the following metronome event; we will call them *reacting* and *aiming* response modes in the sequel. The goals of Exp. 2 were to see (a) whether such synchronization strategies do exist, and (b) what the role of phase correction is and whether its characteristics are consistent with our synchronization model.

We see the problem of synchronization with a stable metronome (i.e., a metronome with a constant mean period) as fundamentally different from the problem of adjusting to changes in the metronome period; this is why the current version of the two-level synchronization model does not incorporate period correction assumptions. Several investigators have studied synchronization performance in tasks with variable metronome periods. Models have been put forward that are based either on period correction only (Michon, 1967) or on both period and phase correction schemes (Mates, 1994a, b; Vos and Helsper, 1992). It has been suggested that a step-like change in the metronome period, after synchronization has been established, is *overcompensated* in the next response cycle. According to this rule, an increase (or decrease) of the metronome period by some value d is predicted to be followed by an IRI that is larger (smaller) than the previous IRI by the amount $2d$. Some experimental results are consistent with this prediction (Michon, 1967; Vos and Helsper, 1992). Nevertheless, we suspect that such stereotyped response trajectories largely reflect contingencies of the experimental context and task. If so, different procedures or tasks might enable subjects to generate more flexible and variable IRI trajectories than is predicted by the overcompensation rule. The present experiment allowed us to examine this possibility.

Method

Subjects. Five new subjects (two females and three males) and the first author participated in the experiment. All subjects were right-handed and used their preferred hand in the tapping task.

Task and design. To reduce tempo variations between subjects, the trials were initiated by 5 metronome clicks paced at 600-ms intervals. Subjects were asked to tap at this tempo, starting shortly after the last click. As in Exp. 1, the IRIs were monitored on-line and their mean was determined. After 35 self-paced taps, the metronome came on again. The first metronome click followed the critical tap with a phase delay of 80%, relative to the mean IRI in this trial. The metronome period was equal to 50%, 80%, 100%, or 150% of the mean IRI. Subjects were informed that the metronome would beat either at the same rate as their own, or at a slower or faster rate. They were asked to join the metronome as smoothly as possible, without interrupting their tapping.

For each subject a total of 64 correct trials were recorded, 16 for each period value. Within a block of 4 trials, each period value was presented once, in random order. Each subject performed the experiment in a single session of about 90 minutes.

Results and discussion

Figures 5 and 6 show the asynchrony and IRI trajectories, averaged over subjects, that were prevalent in this experiment. In the graphs representing IRIs, the leftmost data point corresponds to the IRI bounded by taps 35 and 36; it is generally close to 600 ms. In the graphs representing asynchronies, the leftmost data point corresponds to the asynchrony between the first metronome event and the 36th tap; it is generally close to 120 ms and, by definition, positive. The insets illustrate the temporal relationships between taps and metronome events. White arrowheads without shafts indicate metronome events. Arrows indicate taps: black arrows stand for actual taps, while a white arrow indicates the temporal position where the next tap would occur if the subject had continued at the initial given rate. On the right side of the figures, the frequency of occurrence of the different types of trajectories is given as percentage of (N = 96) trials.

Fig. 5 Mean asynchronies and IRIs under the 50% and 80% period conditions. The insets show the timing relationships between response events (*black arrows*) and metronome events (*white arrowheads*). After 35 self-paced regular taps, tap 36 falls in the first metronome cycle. The *white arrow* indicates the timing position that tap 37 would have without modifications of tap timing. See text for further details

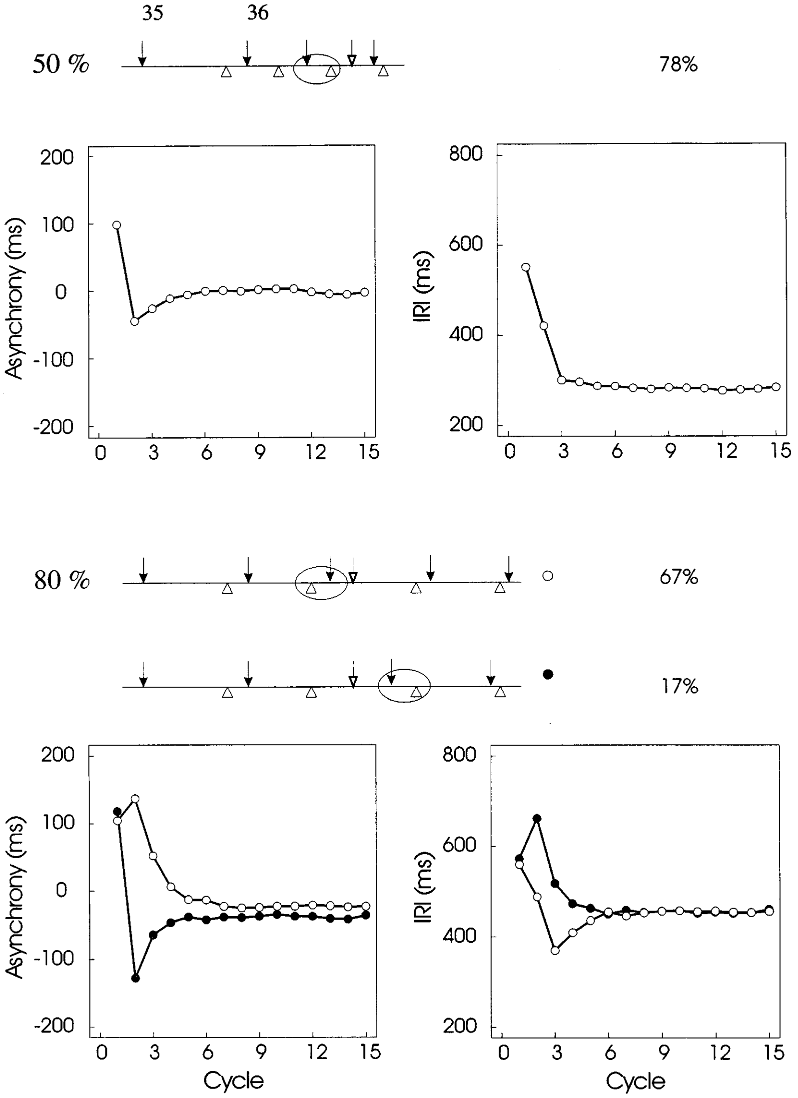
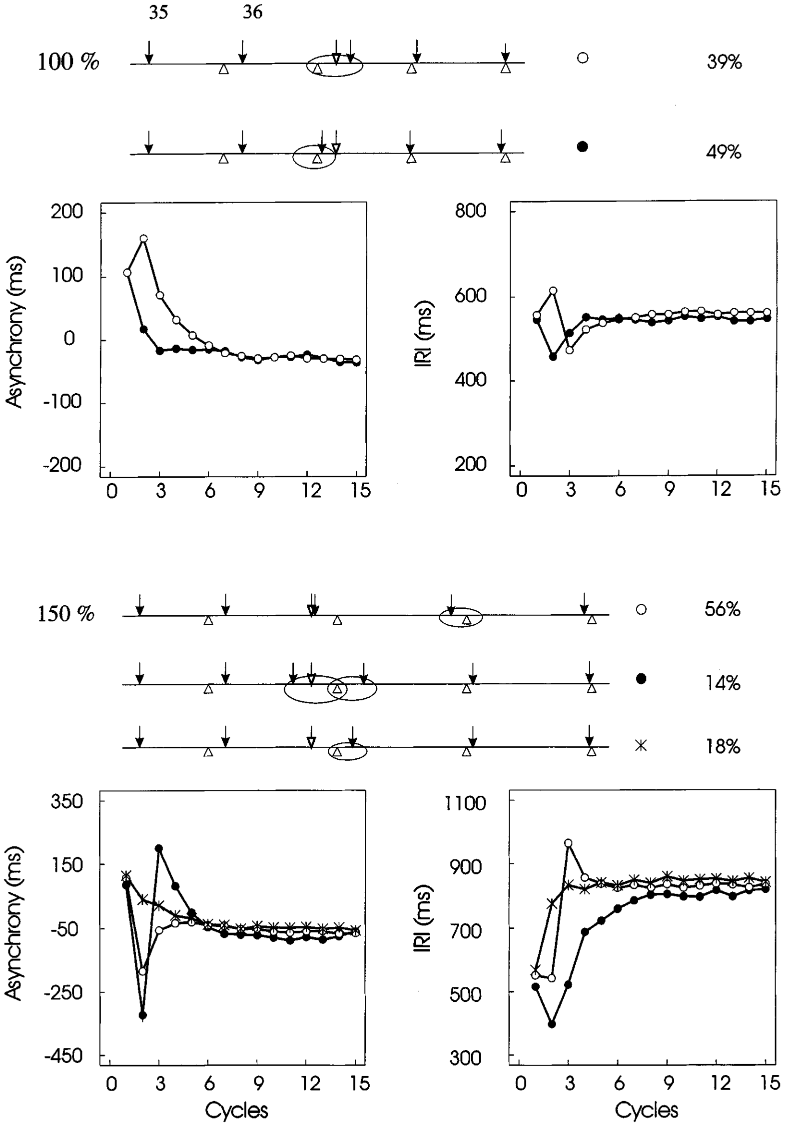


Fig. 6 Mean asynchronies and IRIs under the 100% and 150% period conditions



Under the 50% period condition (Fig. 5, top), the predominant strategy was to put a tap shortly *before* the *third* metronome event (see, on the inset, the encircled tap and metronome event) and to correct the remaining negative asynchrony over the subsequent response cycles. Note that the tap which aims at the anticipated temporal location of the third metronome event terminates an IRI that is shorter than the previous IRI but longer than the metronome interval. Obviously, this is not compatible with the overcompensation hypothesis.

In the 80% period condition, the predominant response mode was to place a tap shortly behind the second metronome event (Fig. 5, bottom, open circles). This response mode entailed shortening the second IRI, and a transient increase of the positive asynchrony. Two subjects, however, produced a few trials in which they delayed this tap beyond the second metronome event (or skipped a tap altogether) such that the second observed tap occurred shortly before the third metronome event. This entailed lengthening the second IRI and shifting from positive to negative asynchrony (Fig. 5, bottom, filled circles).

Under the 100% period condition, all subjects placed tap 37 shortly behind the second metronome event, on most of the trials. Nevertheless, two distinct response modes could be identified. One response mode (Fig. 6, top, open circles) involved lengthening the second IRI and increasing the positive asynchrony, which may be seen as reacting to the second click. The other response mode (Fig. 6, top, filled circles) involved shortening the second IRI and monotonically decreasing the initially positive asynchrony. The small size of the positive asynchrony to the second metronome click makes it unlikely that this indicates a reacting response mode. It is conceivable that the subjects immediately engaged in phase correction here, correctly guessing that the period would remain unchanged.

In the 150% period condition, subjects most often filled in the long period to the second metronome click with a tap (Fig. 6, bottom). This tap terminated an IRI slightly shorter than the previous IRI. Upon the arrival of the second metronome click, the prevalent response mode was aiming at the third metronome click, which entailed a sharp increase in the IRI and a negative asynchrony (see Fig. 6, bottom, open circles). In a second response mode (Fig. 6, bottom, filled circles), subjects produced two taps near the second metronome click (see the double encircling in the inset); they seem to have guessed wrongly that the metronome period would shorten and then reacted to the click just heard, which entailed a relatively short IRI and a positive asynchrony. In the third mode (Fig. 6, bottom, asterisks), the tap was delayed until after the second metronome click, and the subject immediately produced an IRI close to the target period.

In trying to adjust both the timekeeper period and phase, most of the time (78% of the trials) the subjects selected either the second or the third metronome click as reference event; they produced a tap close to it and then began correcting the residual phase error. When the second metronome click served as reference event, the tap occurred shortly after that click; the size of the positive asynchrony suggested that the tap was emitted under the influence of the metronome signal.[1] This reacting strategy was observed more often in the 80% and 100% conditions where the metronome period was close to the initial tapping rate. In contrast, when the third metronome click was used as reference event, the tap occurred shortly *before* that click; the size of the undershoot (negative asynchrony) was inversely related to the length of the updated IRI. This aiming strategy was predominant in the 50% and 150% conditions, where the metronome period differed strongly from the initial tapping rate. Neither strategy permitted stable synchronization at once, but required a few additional tapping cycles.

One of the aims of Exp. 2 was to examine whether this terminal adjustment of the taps to the metronome follows trajectories which are consistent with the two-level synchronization model. Therefore, we fitted the model to the first ten asynchronies observed under the different period (50%, 80%, 100%, 150%) and response mode (reacting, aiming) conditions. As before, we estimated the gain and timekeeper bias parameters, separately for each subject, that gave the least squared deviation from the asynchrony trajectories. The observed mean asynchronies and the asynchronies predicted from the full model are given in Fig. 7, averaged over subjects. Note that the number of subjects contributing to each of the average estimates varies across response modes. The graphs show that the model predicts the observed asynchrony trajectories well, except for the (150%, aiming) condition (Fig. 7, bottom, left). Under the reacting mode (associated with positive initial asynchrony), the median α and β estimates were 0.59 and 0.06, whereas under the aiming mode (associated with negative initial asynchrony), median values of 0.70 and 0.12 were obtained.

The data of Exp. 2 do not allow us to determine whether the choice of the reference event was under the subjects' control. Observations on individual trials suggest that random fluctuations play a major role in determining the response mode. The examples given in Fig. 8 show that asynchrony trajectories which have identical initial histories may bifurcate later. These examples highlight the flexibility of motor organization: Once the response mode is adopted, the sign of the remaining phase error (phase-lag or phase-lead) seems to determine whether asymptotic synchronization is achieved by lengthening or shortening the IRIs.

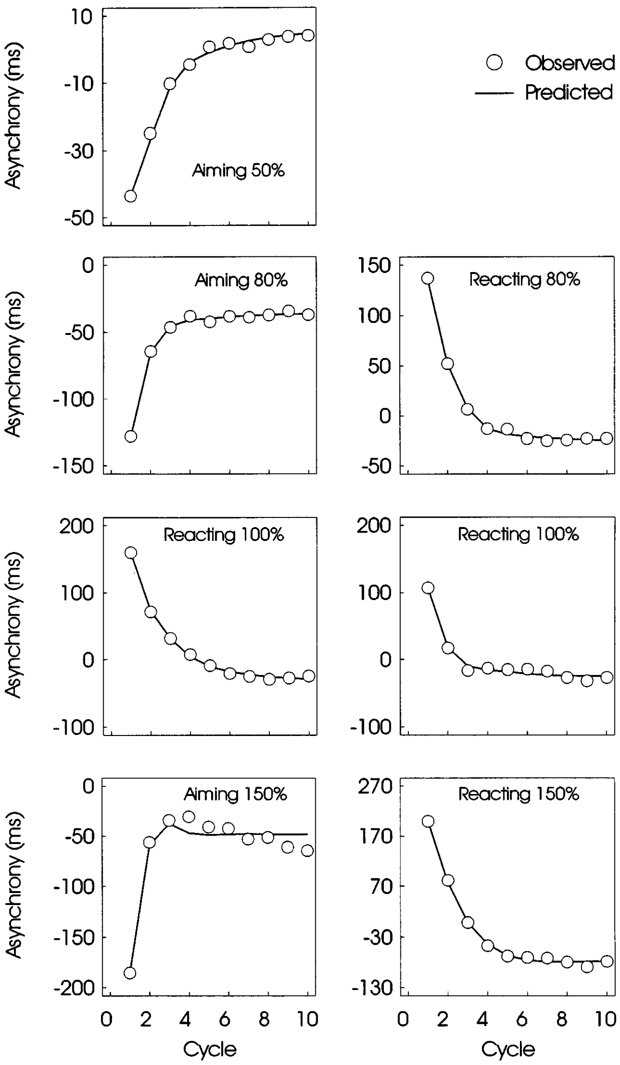


Fig. 7 Observed mean asynchronies, and asynchronies predicted from the full model, during terminal phase adjustment to the metronome, as a function of experimental conditions and mode of responding

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[1] Fraisse (1996) has reported reaction times, in response to extra stimuli presented shortly before the end of the metronome period in synchronization, in the range of 79 to 115 ms.

General discussion

These studies were undertaken within the theoretical framework of the two-level timing model of synchronization (Vorberg & Wing, 1996; Vorberg & Schulze, 1997). Central to this model is the notion that timekeeper intervals are adjusted locally only. Experiment 1 demonstrated that in synchronizing with a stable metronome, the initial phase corrections follow trajectories predicted by the model. Experiment 2 showed that when the task requires a single step-like change in the timekeeper period, synchronization is most often achieved either with reference to the metronome signal which provides sufficient information about the target period, or by anticipating the following metronome event. The inferred alternative strategies imply more variable IRI trajectories than an overcompensation rule predicts. The notion that synchronization involves resetting the timekeeper period plus the ensuing selection of a reference metronome event is more complex than current period correction models have foreseen. This observation alerts us to different possible approaches in modeling phase correction and period correction processes in synchronization.

Phase correction is indispensable in sensory-motor synchronization for preventing the stimulus and response sequences from diverging. Without phase correction, divergence is inevitable if the internal or the external time intervals are affected by random variability. The extended two-level synchronization model admits both first-order and second-order phase adjustment, that is, adjustment of the current timekeeper interval as a function of the last and next-to-last synchronization error. With only first-order phase correction, the asynchrony mean is predicted to approach the asymptote in a geometric fashion, which clearly does not hold under all experimental conditions (see Figs. 4 & 7). Further research is needed to tease out the factors that determine the relative contribution of first-order and second-order phase adjustments. Inter-individual differences seem to play a role, as shown in Exp. 1. For two subjects out of six, the estimated β was vanishingly small (see Table 2), and the fit of the full model was hardly better than that of a model admitting only first-order correction. Tapping rate might be another factor, as parameter estimates based on steady-state synchronization have shown the relative importance of second-order correction to increase for fast tapping rates (Semjen et al., 1997).

While phase correction mechanisms operate on the asynchronies, that is, differences between *time points* of the external and the internally generated events, period correction mechanisms seem to operate on differences between *intervals*, e.g., between the duration of the last timekeeper interval and the duration of the current metronome interval. Synchronization models that assume both phase and period correction (see Mates, 1994a) therefore require simultaneous processing of temporal information in different formats, which may be quite demanding. The results from our second experiment suggest that a phase correction mechanism may achieve synchronization even in a situation that requires a step-like change of the timekeeper period, provided that the sequence of taps catches the sequence of metronome clicks at a suitable reference point. We think that continuously monitoring the metronome intervals and updating the timekeeper period must be assumed to underly synchronization performance only when the metronome is itself subject to continuous period modulations. One aim for further research is to test this hypothesis. Another perspective is offered by the possibility of estimating the phase correction parameters in the transient part in synchronization and to compare them to estimates obtained from synchronization at steady-state. Such comparisons will help to determine whether the correction parameters remain invariant with changes in the size of the synchronization error as our model predicts.

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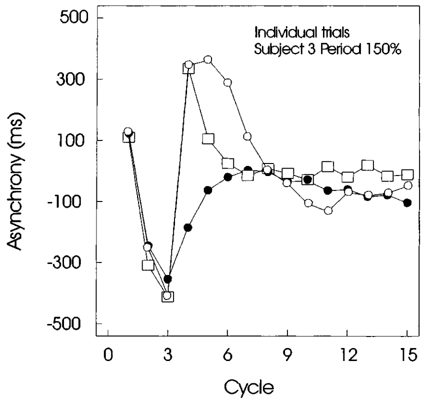

Fig. 8 Asynchrony trajectories in three individual trials of Subject 3 under the 150% period condition

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