

# Phase Correction Following a Perturbation in Sensorimotor Synchronization Depends on Sensory Information

Bruno H. Repp  
Haskins Laboratories  
New Haven, CT

**ABSTRACT.** In models of sensorimotor synchronization, it is generally assumed that phase correction occurs in response to information about sensorimotor asynchrony or relative phase. Without such feedback, a phase perturbation in the motor activity should not be followed by phase correction. Alternatively, internally generated temporal expectations could provide a basis for phase correction in the absence of feedback. To test those hypotheses, the author conducted an experiment in which participants ( $N = 8$ ) tapped their finger in synchrony with isochronous auditory sequences containing a single shifted event onset, after which there could be a gap of up to 3 missing events. Participants were instructed to not react to the shifted event and to continue tapping regularly during any gap. The shifted event caused an involuntary phase shift of the following tap. The shift was corrected if the sequence continued, but during a gap, the shift persisted without correction. Those results confirm that sensory feedback is necessary for phase correction to occur.

*Key words:* feedback, perturbation, phase correction, sensorimotor synchronization

**S**ensorimotor synchronization is a simple skill that is fundamental to human musicality (Trevarthen, 1999–2000) and is apparently unique to humans, at least among mammals (Fraisse, 1974, 1980; Merker, 1999–2000, 2000). It requires three basic processes: (a) an internal timekeeper or oscillator that launches motor commands at appropriate times; (b) a perceptual process that registers the temporal relationship (the asynchrony or relative phase) between the ensuing actions, on the one hand, and an external referent sequence of events, on the other hand; and (c) a corrective process that adjusts the timing of subsequent actions according to the perceived temporal relationship (see, e.g., Pressing, 1999; Vorberg & Wing, 1996). In the laboratory, investigators most often study sensorimotor synchronization by asking participants to tap their finger in synchrony with an auditory metronome.

The error-correction process that enables participants to

stay in synchrony with a metronome is called *phase correction*. It is generally assumed that in the phase-correction process, the temporal intervals generated by the central timekeeper or oscillator are adjusted without permanently altering the timekeeper's period. The magnitude of the adjustment depends on the perceived asynchrony. A simple linear model of phase correction, in which the adjustment to each timekeeper interval is a fixed proportion of the most recent asynchrony (Mates, 1994a, 1994b; Pressing, 1998, 1999; Shaffer, 1981; Vorberg & Schulze, 2002; Vorberg & Wing, 1996), accounts well for the statistical properties of time series data resulting from synchronization with a metronome (Pressing, 1998; Semjen, Schulze, & Vorberg, 2000). Under certain conditions, especially when the tempo is fast or when the performers are trained musicians, the two most recent asynchronies may affect the adjustment (Pressing, 1998; Pressing & Jolley-Rogers, 1997; Semjen, Vorberg, & Schulze, 1998). Synchronization data obtained with sequences containing small random or local perturbations are also generally consistent with the linear phase-correction model (Repp, 2000, 2001a; Schulze, 1992; Vorberg & Schulze, 2002). Pressing (1999) has shown that the linear phase-correction model is a special case of the nonlinear models favored in dynamic systems approaches to sensorimotor coordination. Even in nonlinear models, a linear error-correction function is predicted when asynchronies are relatively small (e.g., Engbert et al., 1997); nonlinearities emerge only when the errors get large (Repp, 2002a, 2002b).

---

*Correspondence address:* Bruno H. Repp, Haskins Laboratories, 270 Crown Street, New Haven, CT 06511-6695, USA. E-mail address: repp@haskins.yale.edu

A fundamental assumption underlying both linear and nonlinear phase-correction models is that information about the sensorimotor asynchrony (or about relative phase, which is the asynchrony divided by the metronome period) is needed before phase correction can occur. In other words, it is predicted in the models that there will be no phase correction if there is no sensorimotor asynchrony. The two following cases must be distinguished here: (a) Available sensory information indicates that the asynchrony is zero so that phase correction is not necessary. Such a situation might occur occasionally during synchronization. (b) There is no sensory information at all so that relative phase is undefined and phase correction is not possible. It has generally been assumed that (b) is the case when a repetitive action occurs freely without an external referent (Vorberg & Wing, 1996; Wing & Kristofferson, 1973).

However, there are other situations in which phase correction seems theoretically possible, even in the absence of information about a sensorimotor asynchrony. In those cases, an internally generated referent might substitute for an absent external one. One such situation is the unexpected perturbation of a periodic motor activity such as finger tapping. The periodicity of the activity itself may induce an expectation for when the next tap is going to occur. If a perturbation causes that tap to occur earlier or later than expected, that disturbance might be registered as an internal asynchrony between the actual and the expected times of the tap's occurrence. In theory, that asynchrony could then lead to a corrective adjustment in timing that brings the following tap back toward the original (extrapolated) phase of the motor rhythm. Another situation is synchronization with an interrupted metronome. Here, information about a sensorimotor asynchrony is expected but does not arrive because of a missing external event. However, the periodicity of the preceding metronome beats induces an expectation for when the next beat is going to occur. That expectation might be compared with the time of occurrence of a tap, and the resulting asynchrony might provide the informational basis for phase correction. In each of those two situations, an internal referent (i.e., a temporal expectation) is induced by an immediately preceding periodic series of actions or events.

Mari Riess Jones (1976; Barnes & Jones, 2000; Jones & Boltz, 1989; Large & Jones, 1999) has long been arguing that the perceptual monitoring of periodic auditory sequences entrains internal oscillators that, in turn, generate temporal expectations. According to Jones's theory, a listener detects a deviation from regularity in a sound sequence by registering an asynchrony between the expected and the actual times of occurrence of a perceptual event. (Jones called that asynchrony *temporal contrast* or *expectancy violation*.) Indeed, it is difficult to see how it could be otherwise. In the spirit of another important theory, that of common coding of perception and action (Hommel, Müssele, Aschersleben, & Prinz, in press; Prinz, 1990), Jones's basic idea can be extended to include asyn-

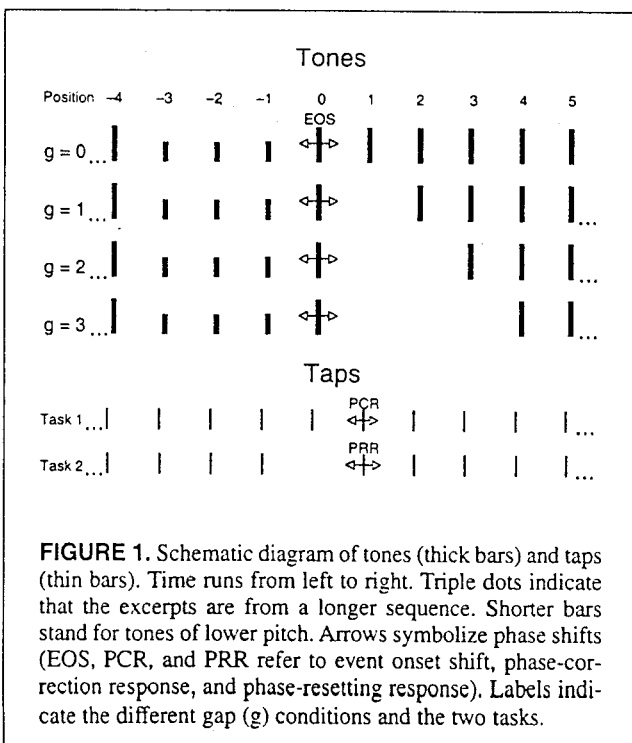
chronies between expectations for perceptual events and actual motor responses, and even between expectations for future actions and either perceived events or actual motor responses (see also Repp, 2001a). In other words, there are two kinds of temporal expectation (for perceptual events,  $E_e$ , and for actions,  $E_a$ ) and two possible perceived occurrences in time (of perceptual events,  $P_e$ , and of actions,  $P_a$ ), and any pairwise combination of those could result in an asynchrony. The ordinary sensorimotor asynchrony is  $P_a - P_e$ , perceptual expectancy violation is  $E_e - P_e$ , and the hypothetical asynchronies of special interest here are  $E_e - P_a$  and  $E_a - P_a$ . Whether those asynchronies play any role in the regulation of behavior is an empirical question.

In the present study, I investigated that issue by perturbing the phase of a tap accompanying an auditory sequence and immediately afterward omitting one or more sequence events in order to see whether the phase shift was corrected during the ensuing gap. I brought about the phase shift in the taps indirectly by using a local phase perturbation in the sequence, following the event onset shift (EOS) paradigm developed in a recent series of experiments (Repp, 2002a). In those experiments, participants were asked to tap in synchrony with isochronous sequences of tones in which a single tone was displaced in time. Following that EOS, the sequence continued in its original phase. Whereas participants must make phase corrections to stay in synchrony with a sequence in which all tones from a certain point on are phase-shifted (Repp, 2000, 2001a), phase correction is neither necessary nor even desirable in the case of an EOS because it causes the following tap to be out of synchrony with the coincident event; therefore, participants must make further phase correction to reestablish synchrony. The best thing to do would be to ignore the EOS and tap steadily, in which case the asynchrony associated with the following tap would be minimal. I showed, however (Repp, 2002a), that participants were unable to carry out that strategy. The EOS caused an involuntary (and usually unnoticed) shift of the following tap. That shift, termed the *phase correction response* (PCR), was always in the same direction as the EOS but of smaller magnitude. Following the PCR, the phase-correction process restored the original phase within a few taps.

In Repp (2002a), I also included a condition in which participants, after hearing a pitch cue, had to withhold the tap that coincided with the EOS. My original motivation for that condition (see Repp, 2001a) was not unlike that in the present study: I hypothesized that, in the absence of a sensorimotor asynchrony ( $P_a - P_e$ ), the asynchrony between the shifted sequence event and its expected time of occurrence ( $E_e - P_e$ ) might serve as a basis for automatic phase correction, leading to an equally large or slightly smaller PCR. Surprisingly, however, the PCR was much larger after a tap was omitted than when tapping was uninterrupted. That finding was attributed to phase resetting of the motor activity with reference to the shifted sequence event, not to phase correction on the basis of an asynchrony. The enhanced

PCR following a skipped tap is referred to herein as a *phase resetting response* (PRR).

Making use of the previous findings, the present experiment comprised two synchronization tasks. In Task 1, continuous tapping was required, whereas in Task 2, participants had to skip the tap that coincided with an EOS in the sequence. After the EOS, the sequence either continued or was interrupted by a gap of up to three missing tones. That design is illustrated schematically in Figure 1. To investigate the possible role of awareness, I used two absolute EOS magnitudes (one readily detectable and the other subliminal). There were two EOS directions (negative and positive). Control sequences without an EOS were also included. Regardless of detectability, an EOS was expected to cause an unintended shift in the following tap. The absolute magnitude of that shift was expected to be larger following a large EOS than following a small EOS, and the PRR in Task 2 was also expected to be larger than the PCR in Task 1. The question of interest was whether any phase correction would be evident during the gaps in the sequence, where there were no sensorimotor asynchronies. According to current models of phase correction, the PCR or PRR caused by the EOS should persist during a gap, and phase correction should occur only when the sequence continues, making sensory feedback available again. By contrast, according to either of the temporal expectancy hypotheses outlined earlier, at least partial phase correction might occur during a gap. Specifically, phase correction might be based on an asynchrony between the perceived shifted tap ( $P_a$ ) and either an expectation for the missing sequence tone ( $E_a$ ) or an expectation for when the tap properly should have occurred ( $E_b$ ).



## Method

### Participants

Seven of the 8 participants (4 women and 4 men) had performed in a number of earlier synchronization experiments and were able to tap with low variability, as was the single newcomer. A wide range of ages (19–55 years) and musical experience (from little training to professional competence) was represented. Six participants were paid for their participation and were naïve about the purpose of the experiment; the other 2 were a research assistant and the author.

### Materials

Tone sequences of varying length were specified by pre-assembled musical instrument digital interface (MIDI) instructions and were generated on a Roland RD-250s digital piano under control of a MAX patch (i.e., program) running on a Macintosh Quadra 660AV computer. The baseline interonset interval between sequence tones was 500 ms.<sup>1</sup> Each sequence contained mainly high-pitched tones (4,186 Hz, sounding like pings), but three successive tones in the interior of each sequence had a lower pitch (2,638 Hz). All tones had sharp onsets followed by rapid decays, a nominal duration of 20 ms (some decay followed the nominal offset), and the same nominal intensity (MIDI key velocity). The three lower tones were followed by the critical tone, whose onset was variable (i.e., the EOS). The critical tone occurred in the 8th, 9th, 10th, 11th, or 12th sequence position. In control sequences, the critical tone occurred at the expected time (EOS = 0). In the other sequences, it was advanced or delayed by 10 or 100 ms. I knew from earlier research (Friberg & Sundberg, 1995; Repp, 2002a) that 10-ms (2%) shifts would not generally be noticed by listeners (the detection threshold is around 4–5%), whereas 100-ms (20%) shifts would be quite obvious. After the EOS, the sequence continued with five additional tones in the original phase, either immediately or after a silent gap resulting from one, two, or three missing tones (see Figure 1).

In all, there were 100 different sequences (5 EOS positions × 5 EOS magnitudes [including zero] × 4 gap conditions [including zero]), which were arranged into five blocks of 20, such that each Magnitude × Gap combination occurred once in each block. The order within blocks was random. A second set of five blocks was constructed so that each Magnitude × Gap combination was presented 10 times in all. Sequences within blocks were separated by 4 s of silence.

### Procedure

Participants sat in front of the computer monitor, which displayed the current trial number. They listened to the sequences over Sennheiser HD540 II earphones and tapped on a Fatar Studio 37 MIDI controller (a silent three-octave piano keyboard) by depressing a white key with the index finger of the preferred hand. The MIDI controller was held on the lap, and I asked participants to move their unsp-

ported tapping arm mainly from the elbow to avoid fatigue in wrist or finger joints. (Individual participants, however, differed in their preferred tapping kinematics.) The response key had a cushioned bottom contact and did not produce any audible impact noise unless it was struck rather hard, which was the case with 3 participants. The electronic registration of a key depression occurred during the downward movement of the key. Participants were instructed to tap in synchrony with the sequence tones, starting with the second tone in each sequence. They were informed that the sequences contained three successive lower-pitched tones and that the immediately following tone might occur too early or too late. They were urged to not let a shifted tone affect their tapping and to continue tapping as regularly as possible, because that would keep them in synchrony with the subsequent tones. (All but 1 participant already had experience with this task from previous experiments.) They were also informed that there would often be a gap following the critical tone, and they were told to tap regularly through the gap, so as to be in synchrony with the remaining tones when the sequence continued.

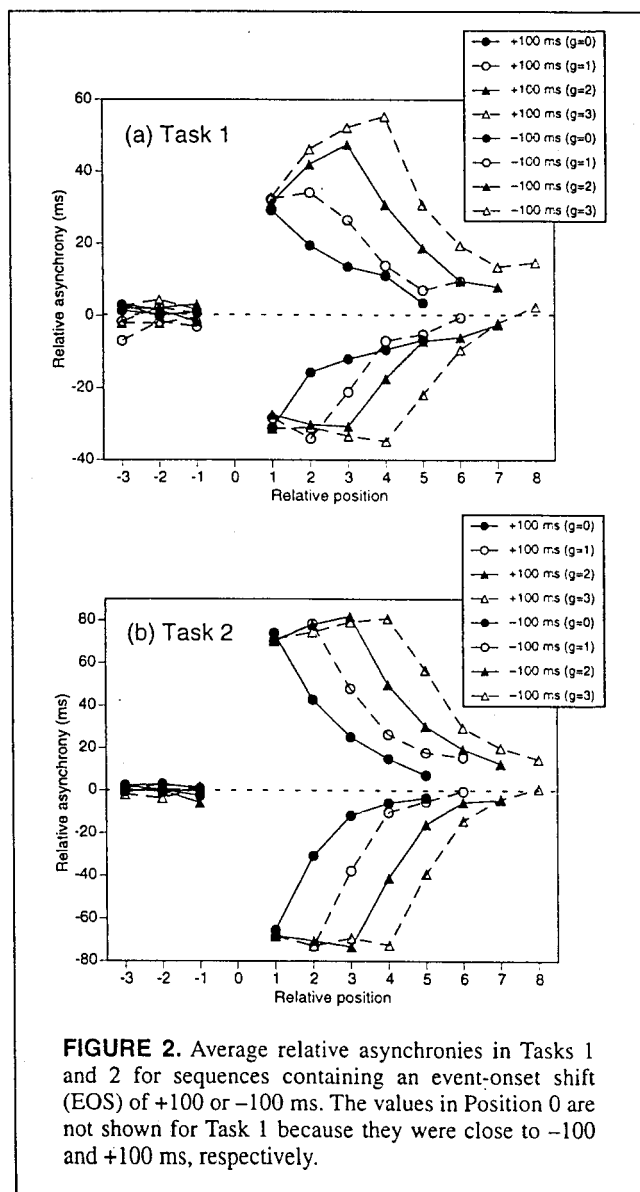
Participants came for two sessions: In the first, Task 1 (continuous tapping) was always performed; and in the second, Task 2 (interrupted tapping). In Task 1, participants were told that the three lower tones were meant to alert them to the upcoming critical tone. In Task 2, which used the same sequences, participants were instructed to omit one tap immediately after hearing the three lower-pitched tones by holding their finger still on the response key and to then continue tapping. It was pointed out that not reacting to a shifted tone in Task 2 implied "coming in at the right time" when tapping resumed. Each session took about 50 min, with short breaks between blocks.

## Results and Discussion

Asynchronies were computed between tone onsets and registered taps, such that a negative asynchrony indicated that the tap preceded the tone. Equivalent virtual asynchronies or, rather, measures of temporal displacement were computed for taps during gaps in the sequence, as if the omitted sequence tone or tones had been present. Several initial taps (the number depending on the position of the EOS) and the final tap in each sequence were excluded from analysis. The results are presented here in terms of absolute or relative asynchronies (in milliseconds). If desired, those values can easily be translated into relative phase measures.

As is commonly found in synchronization tasks, participants' finger taps preceded the sequence tones by some tens of milliseconds (i.e., the asynchronies were generally negative). The grand average asynchrony, computed from the fourth, third, and second pre-EOS taps across all trials and participants, was  $-51$  ms, and individual averages ranged from  $-20$  ms to  $-98$  ms.<sup>2</sup> The anticipation tendency was not of particular interest here (but see, e.g., Aschersleben & Prinz, 1995).

I computed relative asynchronies by subtracting the average asynchronies for the control sequences (discussed later) from those for the perturbed sequences. As a result, the average pre-EOS baseline was close to zero, and any systematic trends in the asynchronies not related to the EOSs themselves were removed. The results for the large EOSs ( $\pm 100$  ms) are presented in Figure 2. Those EOSs were clearly perceivable as temporal irregularities (expectancy violations) in the sequences. For each task, the average relative asynchronies in the four gap (g) conditions were plotted as a function of sequence position, starting three positions before the point at which the EOS occurred (Position 0) and ending 5 to 8 positions later. The relative asynchrony in Position 0 is not shown for Task 1 because it was too large to be accommodated in the graph. (It was near  $-100$  ms for EOSs of  $+100$  ms, and near  $+100$  ms for EOSs of



**FIGURE 2.** Average relative asynchronies in Tasks 1 and 2 for sequences containing an event-onset shift (EOS) of  $+100$  or  $-100$  ms. The values in Position 0 are not shown for Task 1 because they were close to  $-100$  and  $+100$  ms, respectively.

-100 ms.) In Task 2, there was no measurable asynchrony at that point because the tap was omitted.

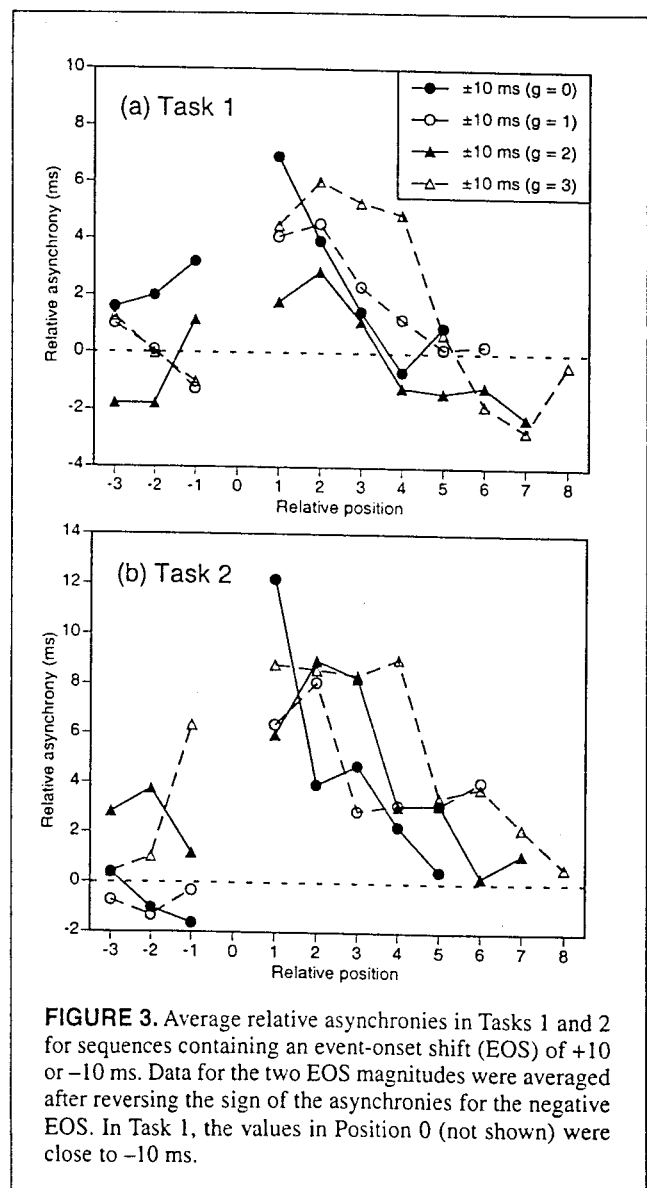
The relative asynchrony in Position 1 represented the involuntary response to the EOS—the PCR (Task 1) or PRR (Task 2). One can see that the average PCR (Figure 2a) was near  $\pm 30$  ms (i.e., about 30% of the EOS), whereas the average PRR (Figure 2b) was near  $\pm 70$  ms (i.e., about 70% of the EOS). Average between-participants standard errors were 5.1 ms and 8.7 ms, respectively. When there was no gap ( $g = 0$ ), the relative asynchronies returned toward the zero baseline in the course of the next few taps, which reflected the ordinary phase-correction process in the presence of sensory feedback. When there was a gap, however, the phase-correction process was clearly delayed, because there was no reduction of relative asynchronies during the gap. That delay was found for both tasks and for both positive and negative EOSs. Four repeated-measures ANOVAs (two tasks and two directions of the EOS) were conducted on Positions 1–5 with the design variables of gap (4) and position (5). All main effects and interactions were highly significant, except for the gap main effect in Task 1 for EOSs of -100 ms,  $F(3, 21) = 2.1, p < .13$ . The delayed phase correction was reflected primarily in the interaction,  $F(12, 84) = 6.2$  to  $24.1$ , all  $ps < .0001$ , which reflected the different time courses of the functions, and secondarily in the gap main effect,  $F(3, 21) = 7.1$  to  $17.5$ , all  $ps < .0001$  (excluding the nonsignificant value reported earlier), which was a consequence of the delays in phase correction. The position main effect,  $F(4, 28) = 18.4$  to  $47.4, p < .0001$ , merely showed that phase correction occurred when sensory feedback was available. (ANOVAs reported later had the same design.)

Because of a concern that the assumptions underlying ANOVA might not have been met by the averaged time series data, an alternative nonparametric statistical test was also conducted. The test was based on the prediction that, because of delayed phase correction, the signed difference between the average relative asynchronies in Positions 1 and 4 should decrease as the duration of the gap increases. That difference was computed for each gap condition, and I assigned each participant a score by awarding 1 point for each pairwise difference among the four conditions that went in the predicted direction and by subtracting 1 point for each difference that went in the opposite direction. The resulting scores, which in theory ranged from -6 to 6, were subjected to one-tailed  $t$  tests. All four  $t$  tests (two tasks and two directions of the EOS) showed the scores to be significantly greater than zero,  $t(7) = 3.5$  to  $13.0$ , all  $ps < .01$ .

One unexpected finding was that the relative tap displacements drifted away from the baseline during gaps following a positive EOS, especially in Task 1 (Figure 2a). Moreover, the relative asynchronies subsequently did not return to zero but seemed to reach an asymptote between 10 and 20 ms. By contrast, the relative displacements of the taps following a negative EOS remained steady during gaps, and the relative asynchronies afterwards returned to zero.

That pattern of results suggests that a positive EOS affected not only the relative phase of the subsequent tap but also the underlying timekeeper or oscillator period, thus somewhat slowing the tempo of the taps. The seemingly incomplete phase correction toward the end of sequences containing a positive EOS might have been caused by persistence of the small period shift (see Repp, 2001b).

In Figure 3, the results for subliminal EOSs ( $\pm 10$  ms) are presented. Those data were quite noisy because the EOS magnitude was smaller than the average standard deviation of the asynchronies. To obtain greater stability, I combined the relative asynchronies for positive and negative EOSs by averaging them after reversing the sign of the responses to negative EOSs. The resulting data, although still variable, showed clear PCRs and PRRs (with average between-participants standard errors of 2.3 ms and 2.1 ms, respectively) as well as definite signs of delayed phase correction during gaps in both tasks. Note especially the contrast between the initial



**FIGURE 3.** Average relative asynchronies in Tasks 1 and 2 for sequences containing an event-onset shift (EOS) of +10 or -10 ms. Data for the two EOS magnitudes were averaged after reversing the sign of the asynchronies for the negative EOS. In Task 1, the values in Position 0 (not shown) were close to -10 ms.

decrease of the function for  $g = 0$  and the initial plateau across Positions 1–4 of the function for  $g = 3$ . In repeated measures ANOVAs on those data, the Gap  $\times$  Position interaction approached significance for Task 1,  $F(12, 84) = 1.8, p < .07$ , and was reliable for Task 2,  $F(12, 84) = 3.3, p < .0008$ . The position main effect was significant in both tasks,  $F(4, 28) = 9.8$  and  $15.8$ , respectively, both  $ps < .0001$ , but the gap main effect was not. Student's  $t$  tests conducted on the basis of the scoring method described earlier were significant for both tasks,  $t(7) = 5.3, p < .001$ , and  $t(7) = 3.1, p < .01$ , respectively. Those results were entirely consistent with the main results shown in Figure 2.

Finally, in Figure 4, the average absolute asynchronies for the isochronous control sequences in the two tasks are presented. I omitted from Figure 4a the asynchrony in Position 0 (which was similar to the immediately preceding and following asynchronies) to make the appearance of the graph consistent with the preceding figures. Neither the lower pitch of the warning tones in Positions  $-3$  to  $-1$  nor the gaps as such had much of an effect on the timing of the taps in Task 1. There were no significant effects in the ANOVA on those data.

A quite different picture emerged for Task 2 (see Figure 4b). The omission of the tap in Position 0 clearly affected the asynchronies, as had been observed previously (Repp, 2001a, 2002a). In Position  $-1$ , a preparatory reduction of

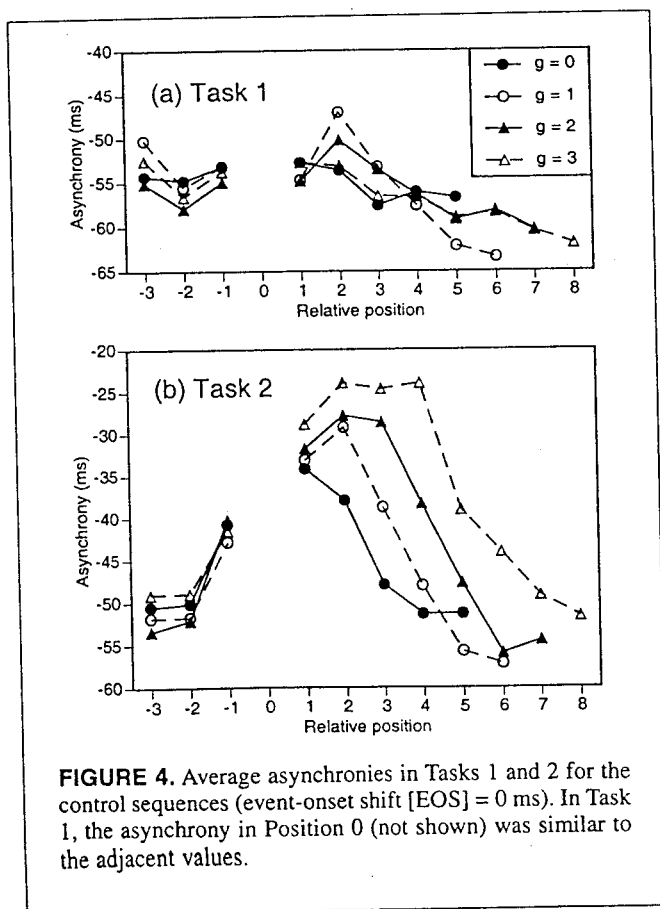
the asynchrony can already be seen. When tapping resumed in Position 1, the asynchronies were less negative by about 20 ms. In the  $g = 0$  condition, the asynchronies returned to the baseline within three taps. However, the phase correction was clearly delayed in the three gap conditions until the sequence tones resumed. That finding (an unanticipated bonus!) extended the main results by suggesting that sensory feedback is also needed for the correction of phase shifts that originate in movement planning rather than in sensorimotor coordination. A repeated-measures ANOVA on those data revealed significant main effects of gap,  $F(3, 21) = 4.1, p < .02$ , and position,  $F(4, 28) = 3.1, p < .03$ , as well as a significant interaction,  $F(12, 84) = 1.9, p < .05$ . A  $t$  test based on the scoring method described above fell just short of significance,  $t(7) = 1.8, p < .06$ .

## Discussion

The present results confirm a basic assumption underlying both stochastic (linear) and dynamic (nonlinear) models of phase correction in synchronization: namely, that information about sensorimotor asynchrony or relative phase is necessary for phase correction to occur. When that information is absent, the current phase of the motor activity is maintained until sensory feedback becomes available. Evidence of that effect was also seen in data from a recent study by Large, Fink, and Kelso (2002) in which participants synchronized with complex rhythmic sequences containing gaps, although Large et al. did not draw attention to that aspect of their data.

The main conclusion is not weakened by the fact that positive phase drift of taps occurred during gaps following large positive EOSs. Because the drift was in a direction away from the baseline, it can hardly have been caused by a phase-correction process. Rather, it seems to reflect a slight lengthening of the internal timekeeper period that governs the rate of tapping. Whenever a positive EOS preceded a gap, the lengthened interonset interval preceding the shifted event was not neutralized by a subsequent shortened interval, as it otherwise would have been, and that imbalance seems to have engaged the period-correction process slightly (see also Repp, 2001a, 2001b). It remains unclear why large negative EOSs did not have a similar effect.

Two secondary findings were consistent with the main results obtained with sequences containing large EOSs. First, sequences containing subliminal EOSs yielded a pattern of responses that, despite considerable variability, was in agreement with the main findings. It should be noted that I included the subliminal EOSs only in view of the theoretical possibility that phase correction would occur during gaps following large EOSs. Such phase correction could have been caused by participants' awareness of the EOSs or of their own PCRs and PRRs, and, in that case, the results for subliminal EOSs would have been of special interest. Because no phase correction during gaps was observed following large EOSs, however, the results for subliminal



EOSs were essentially redundant. There is no conceivable theoretical reason why phase correction in the present task should occur in the absence of awareness if it does not occur in the presence of awareness. The other secondary result, for the control sequences with omitted taps, was not redundant. That finding suggests that the conclusions reached for phase shifts caused by EOSs also apply to phase shifts caused by a change in movement strategy. In other words, the cause of the phase shift does not seem to matter; all that matters is whether sensory information is available following the phase shift.

The results of this study offer no support for the two temporal expectancy hypotheses derived from Jones's (1976) perceptual theory by extending it to perception-action relationships. To recapitulate, according to those hypotheses, participants might base phase correction on an asynchrony between the perceived time of occurrence of the tap exhibiting the PCR or PRR,  $P_a$ , and the expected time of occurrence of either the absent tone in the sequence,  $E_e$ , or the tap itself,  $E_a$ . Although a finding of phase correction during gaps would have been ambiguous with regard to which of those two hypotheses should be favored, the negative result obtained rules out both hypotheses at once. That does not mean that asynchronies of the hypothesized kind do not exist, but if they do exist they apparently cannot serve as the basis of phase correction in action. The existence or usefulness of asynchronies of the second type ( $E_a - P_a$ ) is perhaps doubtful in view of the central and peripheral timing variability that would be reflected in any temporal expectancies based on the motor activity itself. Asynchronies of the first type ( $E_e - P_a$ ) remain plausible, however, because temporal expectancies for events in a sequence certainly do exist. There may be two reasons, then, why they are of little use to the phase-correction process in action. One possibility is that there is no communication between the processes governing perceptual expectation and those governing motor control. That possibility would seem disappointing from the viewpoint of a common-coding theory of perception and action (Hommel et al., in press; Prinz, 1990). The other, more interesting possibility is that an EOS affects temporal expectations in the same way that it affects action timing. Such a perceptual PCR or PRR is predicted by a dynamic theory of attention (Large & Jones, 1999) and appears to be confirmed by recent perceptual experiments (Barnes & Jones, 2000). Thus, the tap exhibiting the PCR or PRR may have been perceived to occur just at the time when the missing tone was expected to occur, yielding an average asynchrony ( $E_e - P_a$ ) of zero. Dynamic attending, conceptualized as a form of internal synchronization with phase and period correction capabilities (Large & Jones, 1999), may be fundamentally similar to sensorimotor synchronization—a parallel that should be explored more thoroughly.

If that interpretation is correct, it leads to the interesting conclusion that one cannot extrapolate the beat of a rhythm correctly beyond a phase-shifted event: A phase shift seems to be obligatory in both perceptual expectation and action.

That notion may have some implications for music performance (see, e.g., Epstein, 1995), although it remains to be seen whether the present results, which were obtained with unstructured sequences, can be generalized to more complex rhythmic or musical sequences that can be organized in terms of a metrical hierarchy.

Although the present results seem to show that information about sensorimotor asynchrony or relative phase is crucial to phase correction, that is not the only possible interpretation of the results. Before linear phase-correction models based on asynchronies became popular in the 1990s, Shaffer (1982) and Hary and Moore (1985, 1987) discussed two discrete phase-resetting processes in synchronization, neither of which requires information about asynchronies. In one process, each tap is timed relative to the preceding tap; in the other process, each tap is timed relative to the preceding sequence event. Those two processes result in zero phase correction and perfect (immediate) phase correction, respectively. After Schulze (1992) demonstrated that probabilistic alternation of the two phase-resetting processes, as envisioned by Hary and Moore, is formally equivalent to imperfect (gradual) phase correction based on asynchronies, there has been little discussion of discrete phase resetting. However, Repp (2001a) tried to revive that notion by arguing that phase correction is imperfect because of a dynamic competition (rather than a probabilistic alternation) between the two phase-resetting processes. That view is consistent with the difference in magnitude between the PCR and the PRR: When a tap is omitted (Task 2), the next tap is timed relative to the last sequence event, hence, the PRR. When there is no interruption of the motor activity (Task 1), the preceding tap and the preceding sequence event jointly determine the timing of the next tap. The present findings are also consistent with that phase-resetting model: When there is no preceding sequence event, a tap is timed relative to the preceding tap, which means that phase correction cannot occur. Therefore, the present findings do not prove that information about asynchronies or relative phase is crucial. The informational basis of phase correction may simply be the times of occurrence of previous events and actions, which provide independent and competing points of reference for the timing of the next action. Reference to time points ( $P_e$ ,  $P_a$ ), rather than differences between time points ( $P_a - P_e$ ), would also explain why phase correction is independent of the conscious detection of perturbations and asynchronies (Repp, 2000).

#### ACKNOWLEDGMENTS

This research was supported by National Institutes of Health Grant MH-51230. I am grateful to Yoko Hoshi for assistance and to Mari Riess Jones and Amandine Penel for helpful discussions and comments.

#### NOTES

1. Because of a peculiarity of the MAX software, the tempo of the output was 2.4% faster than is specified in the MIDI instructions. Thus, the baseline interonset interval was actually 488 ms, and the participants' key presses were registered at a correspond-

ingly slower rate. For convenience, however, all millisecond values are reported here as they appeared in the MAX environment. Apart from the constant scaling factor, MAX was highly accurate (within 1 ms) in timing the sequences and registering the key presses.

2. Because key depression was registered during the downward movement of the response key, the negative asynchrony might have been increased by up to -20 ms, depending on the average key velocity.

## REFERENCES

- Aschersleben, G., & Prinz, W. (1995). Synchronizing actions with events: The role of sensory information. *Perception & Psychophysics*, *57*, 305-317.
- Barnes, R., & Jones, M. R. (2000). Expectancy, attention, and time. *Cognitive Psychology*, *41*, 254-311.
- Engbert, R., Scheffczyk, C., Krampe, R. T., Rosenblum, M., Kurths, J., & Kliegl, R. (1997). Tempo-induced transitions in polyrhythmic hand movements. *Physical Review E*, *56*, 5823-5833.
- Eppstein, D. (1995). *Shaping time: Music, the brain, and performance*. Cambridge, MA: MIT Press.
- Fraisse, P. (1974). Cues in sensori-motor synchronization. In L. E. Scheving, F. Halberg, & J. E. Pauly (Eds.), *Chronobiology* (pp. 517-522). Tokyo: Igaku Shoin.
- Fraisse, P. (1980). Les synchronisations sensori-motrices aux rythmes. [Sensorimotor synchronization with rhythms]. In J. Requin (Ed.), *Anticipation et comportement* (pp. 233-257). Paris: Centre National.
- Friberg, A., & Sundberg, J. (1995). Time discrimination in a monotonic, isochronous sequence. *Journal of the Acoustical Society of America*, *98*, 2524-2531.
- Hary, D., & Moore, G. P. (1985). Temporal tracking and synchronization strategies. *Human Neurobiology*, *4*, 73-77.
- Hary, D., & Moore, G. P. (1987). Synchronizing human movement with an external clock source. *Biological Cybernetics*, *56*, 305-311.
- Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (in press). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*.
- Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review*, *83*, 323-335.
- Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, *96*, 459-491.
- Large, E. W., Fink, P., & Kelso, J. A. S. (2002). Tracking simple and complex sequences. *Psychological Research*, *66*, 3-17.
- Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How we track time-varying events. *Psychological Review*, *106*, 119-159.
- Mates, J. (1994a). A model of synchronization of motor acts to a stimulus sequence. I. Timing and error corrections. *Biological Cybernetics*, *70*, 463-473.
- Mates, J. (1994b). A model of synchronization of motor acts to a stimulus sequence. II. Stability analysis, error estimation and simulations. *Biological Cybernetics*, *70*, 475-484.
- Merker, B. (1999-2000). Synchronous chorusing and the origins of music. *Musicae Scientiae* (Special Issue), 59-73.
- Merker, B. (2000). Synchronous chorusing and human origins. In N. L. Wallin, B. Merker, & S. Brown (Eds.), *The origins of music* (pp. 315-327). Cambridge, MA: MIT Press.
- Pressing, J. (1998). Error correction processes in temporal pattern production. *Journal of Mathematical Psychology*, *42*, 63-101.
- Pressing, J. (1999). The referential dynamics of cognition and action. *Psychological Review*, *106*, 714-747.
- Pressing, J., & Jolley-Rogers, G. (1997). Spectral properties of human cognition and skill. *Biological Cybernetics*, *76*, 339-347.
- Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann & W. Prinz (Eds.), *Relationships between perception and action* (pp. 167-201). Berlin: Springer-Verlag.
- Repp, B. H. (2000). Compensation for subliminal timing perturbations in perceptual-motor synchronization. *Psychological Research*, *63*, 106-128.
- Repp, B. H. (2001a). Phase correction, phase resetting, and phase shifts after subliminal timing perturbations in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 600-621.
- Repp, B. H. (2001b). Processes underlying adaptation to tempo changes in sensorimotor synchronization. *Human Movement Science*, *20*, 277-312.
- Repp, B. H. (2002a). Automaticity and voluntary control of phase correction following event onset shifts in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 410-430.
- Repp, B. H. (2002b). Phase correction in sensorimotor synchronization: Nonlinearities in voluntary and involuntary responses to perturbations. *Human Movement Science*, *21*, 1-37.
- Schulze, H.-H. (1992). The error correction model for the tracking of a random metronome: Statistical properties and an empirical test. In F. Macar, V. Pouthas, & W. J. Friedman (Eds.), *Time, action, and cognition* (pp. 275-286). Dordrecht, The Netherlands: Kluwer.
- Semjen, A., Schulze, H.-H., & Vorberg, D. (2000). Timing precision in continuation and synchronization tapping. *Psychological Research*, *63*, 137-147.
- Semjen, A., Vorberg, D., & Schulze, H.-H. (1998). Getting synchronized with the metronome: Comparisons between phase and period correction. *Psychological Research*, *61*, 44-55.
- Shaffer, L. H. (1982). Rhythm and timing in skill. *Psychological Review*, *89*, 109-122.
- Trevarthen, C. (1999-2000). Musicality and the intrinsic motive pulse: Evidence from human psychobiology and infant communication. *Musicae Scientiae* (Special Issue), 155-215.
- Vorberg, D., & Schulze, H.-H. (in press). Linear phase correction in synchronization: Predictions, parameter estimation, and simulations. *Journal of Mathematical Psychology*, *46*, 56-87.
- Vorberg, D., & Wing, A. (1996). Modeling variability and dependence in timing. In H. Heuer & S. W. Keele (Eds.), *Handbook of perception and action* (Vol. 2, pp. 181-262). London: Academic Press.
- Wing, A., & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses. *Perception & Psychophysics*, *14*, 5-12.

Submitted March 5, 2001

Revised July 27, 2001