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Automaticity and Voluntary Control of Phase Correction Following Event Onset Shifts in Sensorimotor Synchronization

Bruno H. Repp
Haskins Laboratories

Seven experiments show that an event onset shift (EOS) in an auditory sequence causes an involuntary phase correction response (PCR) in synchronized finger tapping. This PCR is (a) equally large in inphase and antiphase tapping; (b) reduced but still present when the EOS occurs in either of two interleaved (target–distractor) sequences; (c) unaffected by increased pitch separation between these sequences; (d) asymptotic in magnitude as EOS magnitude increases, unlike the intentional PCR to expected phase shifts; and (e) enhanced when the EOS precedes the onset of tapping, because of phase resetting. Thus, phase correction is revealed to be partially automatic and partially under voluntary control, and to be based mainly on temporal information derived from simple onset detection.

Sensorimotor synchronization, especially finger tapping in time with an auditory sequence, is a standard paradigm for the investigation of perception–action coordination and error correction processes. The large majority of studies in this area has used isochronous (stationary) sequences and has focused on analysis and modeling of the resulting time series data (e.g., Chen, Ding, & Kelso, 1997; Pressing, 1998; Pressing & Jolley-Rogers, 1997; Semjen, Schulze, & Vorberg, 2000). Using stationary sequences, researchers have also examined the effects of variables such as rate and sensory feedback on the average magnitude and variability of asynchronies (e.g., Aschersleben & Prinz, 1997; Mates, Radil, Müller, & Pöppel, 1994; Mates, Radil, & Pöppel, 1992). Some studies have used nonstationary sequences whose timing varied systematically or randomly and have analyzed how this global variation is reflected in the timing of the synchronized motor response (e.g., Hary & Moore, 1987; Michon, 1967; Thaut, Tian, & Azimi-Sadjadi, 1998). An alternative approach is to introduce local perturbations in the timing of an isochronous sequence and to observe, usually by averaging over repeated trials, how the motor behavior adjusts to these perturbations (e.g., Hary & Moore, 1985; Repp, 2000, 2001a; Thaut, Miller, & Schauer, 1998). This approach, of which the present study is an example, offers some interesting and little-explored possibilities. Of course, all these methods are complementary and are expected to shed converging light on the processes underlying sensorimotor coordination.

Figure 1 illustrates three basic types of local perturbation one can introduce in an isochronous sequence of events. Each framed panel shows successive interonset intervals (IOIs) as a function of position in the sequence, and the display above each panel shows event onsets as a function of time. The first perturbation type is a *phase shift* (or pulse change; Michon, 1967); it consists of a single lengthened or shortened IOI. The second type is a tempo change or *step change* (Michon, 1967); here, all IOIs from the perturbation point (P) onward are lengthened or shortened by the same amount. The third type is a single *event onset shift* (EOS), which results in the complementary lengthening and shortening (or vice versa) of two successive IOIs. Note that all three types of perturbation are identical at P; they are distinguished only by what follows.

Models of error correction (a process also referred to as adaptation, adjustment, compensation, or relaxation) in synchronized tapping have often assumed that there are two independent underlying processes: phase correction and period correction (Mates, 1994a, 1994b; Repp, 2001a; Vorberg & Wing, 1996; Vos & Helsper, 1992; see Large & Jones, 1999, for analogous assumptions in a dynamic model of attention). *Phase correction* adjusts the times at which taps are made without modifying the period of the timekeeper that paces the motor activity. *Period correction* adjusts the timekeeper period. Because both error correction processes affect when a tap is made, they affect the asynchronies between taps and sequence events as well as the intertap intervals (ITIs). Moreover, they affect these variables in the same way. Therefore, the observable behavior is generally ambiguous with regard to the underlying error correction processes (see Repp, 2001a).

Thus, although compensation for a phase shift (Figure 1a) can be achieved by means of phase correction alone, it could just as well be accomplished by means of transient period correction, implausible as this may seem. However, a recent study (Repp, 2001a, Experiment 1), in which the ITIs of continuation tapping were used as an index of the state of the internal timekeeper period following a phase shift, has provided evidence that phase shifts engage mainly the phase correction process, at least as long as the change is small and no tempo change is expected (see also Repp, 2001b). A series of perturbation studies (Repp, 1999, 2000, 2001a) has suggested that phase correction is an automatic, usually subconscious process that operates effectively below the perceptual detection threshold.

By contrast, a step change (Figure 1b) seems to require period correction, although in principle the taps could keep pace with the

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Correspondence concerning this article should be addressed to Bruno H. Repp, Haskins Laboratories, 270 Crown Street, New Haven, Connecticut 06511–6695. E-mail: repp@haskins.yale.edu

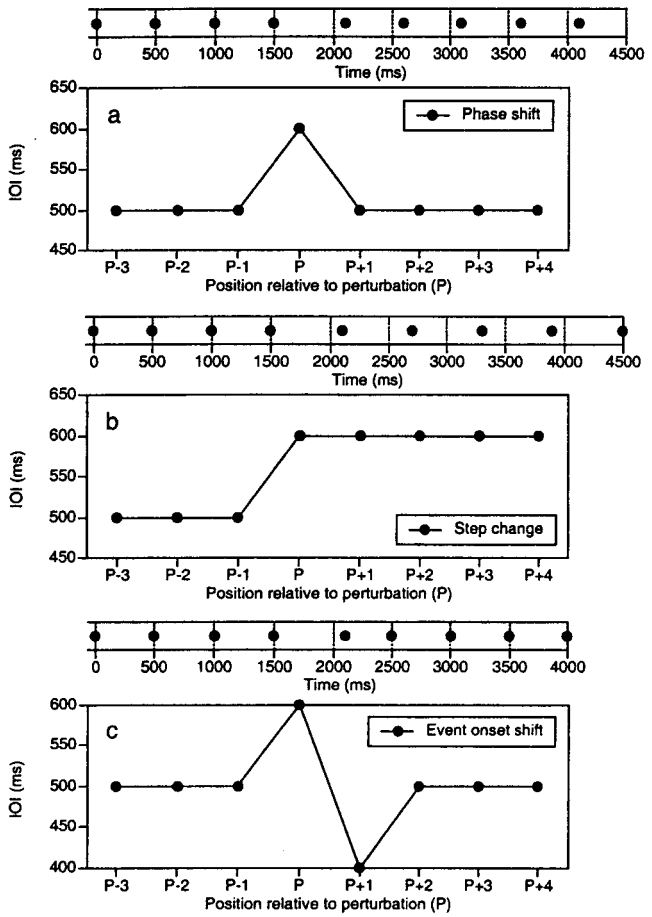

Figure 1. Three kinds of local perturbation in isochronous sequences: (a) phase shift, (b) step change (tempo change), and (c) event onset shift. The display above each panel shows event onsets as a function of time; the panel itself shows interonset interval (IOI) duration as a function of sequence position.

tones by means of repeated phase correction. Indeed, this is exactly what seems to happen when the step change is below the perceptual detection threshold (Hary & Moore, 1985, 1987; Thaut, Miller, et al., 1998). Period correction seems to require, or is at least facilitated by, awareness of a tempo change (Repp, 2001b). However, phase correction is always needed in conjunction with period correction. Because a phase shift and a step change are identical at the perturbation point P (see Figure 1), it is likely that automatic phase correction will be elicited initially by both, with period correction kicking in as a step change becomes evident. This simultaneous engagement of both processes leads to initial overcorrection of the ITIs (Mates, 1994a; Michon, 1967; Repp, 2001b; Thaut, Miller, et al., 1998).

There do not seem to be any previous investigations of the effects of EOSs (Figure 1c) on synchronization behavior, although the perceptual detectability of EOSs has been studied repeatedly (e.g., Brochard, Drake, Botte, & McAdams, 1999; Hibi, 1983; Hirsh, Monahan, Grant, & Singh, 1990; Jones & Yee, 1997; Schulze, 1978; Vos, Assen, & Franek, 1997). The likely reason for this neglect is that, unlike phase shifts and step changes, EOSs do not seem to require any corrective action because there is neither a phase shift nor a tempo change in the sequence beyond P. The optimal strategy would be to ignore the perturbation and to keep tapping as regularly as possible. However, in view of the fact that an EOS is indistinguishable from a phase shift or step change at P (Figure 1), it seems likely that an EOS, too, would elicit a phase correction, even though this constitutes nonoptimal behavior in that situation. To the extent that phase correction is an automatic, subconscious process, it should be unavoidable, even if participants know that all perturbations encountered will be of the EOS type and even if they try hard not to react to them.

The observable manifestation of phase correction in response to an EOS is a shift in the relative timing of the immediately following tap. In this article, this shift is called the *phase correction response* (PCR). If a PCR occurs in response to an EOS, it causes an asynchrony, so that further phase correction is required to restore synchrony on subsequent taps. That additional phase correction was of less interest here, as it depended on the PCR; the PCR itself was of primary interest. The present experiments investigated the PCR to both subliminal and supraliminal EOSs. When an EOS is subliminal, it seems unlikely that phase correction will be affected by a participant's intention not to react. Thus, the PCR was expected to be the same as for a phase shift of the same magnitude. However, when an EOS is detectable, voluntary control over the magnitude of the PCR may become possible, leading to three theoretical outcomes: (a) complete suppression of the PCR, which would suggest control over the internal phase correction process itself; (b) a proportional reduction of the PCR, which would suggest partial control over the internal process (e.g., a gain parameter); (c) an asymptotic limit to the PCR as EOS magnitude increases, which would suggest control over some other process that impinges on phase correction. A fourth possibility is that there is no effect of voluntary control.

A variety of other factors that might affect the magnitude of the PCR was investigated in seven experiments. They included marking the shifted tones (Experiment 1), providing auditory feedback from the taps (Experiment 2), tapping at a distance from the EOSs (Experiments 2–4), providing an isochronous reference sequence (Experiments 3–4), varying the pitch distance between two interleaved sequences (Experiments 3–4), and (re)starting to tap immediately after an EOS (Experiment 7). Some of these factors were expected to reduce the PCR, whereas others were expected to increase it, as explained in more detail in the introductions to the individual experiments. Experiment 5 was a detailed investigation of the relationship between EOS and PCR magnitudes, and Experiment 6 collected analogous data with phase shifts for comparison. All experiments required synchronized finger tapping with auditory tone sequences, and the (moderately trained) participants were always instructed to tap as regularly as possible and not to react to any EOSs in the sequences.

Experiment 1

The aim of Experiment 1 was to address the basic hypothesis that phase correction is an automatic process, which implies that a PCR to an EOS is unavoidable (at least without extensive training, which was not provided here). EOSs of two magnitudes were introduced, one subliminal (i.e., very difficult to hear) and the other supraliminal (i.e., easy to hear), according to pilot observa-

tions and psychophysical data in the literature (e.g., Friberg & Sundberg, 1995). The questions of main interest were first, whether a PCR would occur in both subliminal and supraliminal conditions and second, whether the respective PCRs would be proportional to the magnitude of the EOS or whether the PCR in the supraliminal condition would represent a smaller proportion of the EOS, which might indicate a voluntary reduction of the PCR. Possible asymmetries in the PCRs to positive and negative EOSs were also of interest, though there were no specific expectations in that regard. Phase correction in response to phase shifts seems to exhibit little asymmetry (Repp, 2000, 2001a).

One additional factor was introduced in Experiment 1: The shifted tone either had the same pitch as the other sequence tones or was distinguished by a much lower pitch. This manipulation was expected to have three independent effects, each potentially leading to a reduced PCR: First, a change in pitch draws attention to the location of each perturbation. Second, in sequences containing four evenly spaced EOSs, as used in Experiment 1, the earlier marked tones may enable participants to predict the locations of later EOSs in the sequence. Third, the large pitch difference may segregate the shifted tone from the stream of higher-pitch tones, and this in turn may impede the perception of its timing relative to the surrounding tones (Bregman, 1990; Jones, 1976; Jones, Jagacinski, Yee, Floyd, & Klapp, 1995; Thorpe & Trehub, 1989; Thorpe, Trehub, Morrongiello, & Bull, 1988). There is evidence, however, that phase correction in response to phase shifts is independent of perceptual judgments of timing (Repp, 2000). One experiment in that same study demonstrated that a pitch change in the sequence had no effect on phase correction, even though it did have an effect on the detection threshold. Therefore, it seemed quite possible that the present pitch difference, even though it was much larger than in the earlier experiment, would likewise have no effect on phase correction.

Method

Participants. There were 8 participants, 6 of whom were fairly practiced in synchronized tapping, having served in a number of previous experiments. They included myself (male, age 54), a postdoctoral researcher (female, age 26), 2 research assistants (male, age 38; female, age 22), and 4 paid volunteers (2 men about 30 years old and 2 women about 19 years old). Four of the participants had substantial musical training.

Stimuli. The tone sequences were produced on a Roland RD-250s digital piano via a musical instrument digital interface (MIDI) under control of a MAX patch running on a Macintosh Quadra 660AV computer.[1] A sequence (trial) consisted of 50 tones with a baseline IOI of 500 ms. The tones (sounding more like pings) were of very high pitch (C_8: 4168 Hz), had sharp onsets, and decayed rapidly; their nominal duration was 20 ms. Each sequence contained four tones whose onsets were shifted by the same amount of time (Δt) and were separated by nine unperturbed tones. The Δt values were +10 or −10 ms (subliminal) and +50 or −50 ms (supraliminal). The average detection threshold for such shifts tends to be near ±20 ms (Friberg & Sundberg, 1995; see also Experiment 5, below), and none of the participants spontaneously reported hearing any irregularities in the timing of the sequences containing EOSs with Δt equal to ±10 ms. For each of the four Δt values, there were 10 trials, with the position of the first EOS varying from the 6th to the 15th sequence position. Thus, there were 40 different sequences altogether that were arranged into four blocks of 10 trials each. The first two blocks contained EOSs of ±10 ms, and the second two contained EOSs of ±50 ms. Positive and negative EOSs alternated from trial to trial within each block. The trials were in random order with regard to the position of the first EOS. A second set of four blocks was identical, except that the shifted tone had a much lower pitch (E_4: 330 Hz, 20-ms nominal duration) than the other tones.

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 in synchrony with the sequence tones. The MIDI controller was held on the lap, and participants were encouraged to move the unsupported 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 sound unless it was struck rather hard (as may have been the case with some individual participants). The electronic registration of a key depression occurred during the downward movement of the key. Participants were instructed to start tapping with the second tone in each sequence.

The eight blocks of trials were presented in a fixed order. For the first two blocks (subliminal EOSs), the task was simply to tap in synchrony with the (seemingly isochronous) tone sequences. For the next two blocks (supraliminal EOSs), the participants were informed that noticeable EOSs would occur, but they were urged not to react to them and to tap as regularly as possible during these perturbations. It was explained that this strategy would lead to synchrony after the EOS. Analogous instructions were given for the remaining four blocks, except that the participants were told that "four tones" (Blocks 5 and 6) or "the shifted tones" (Blocks 7 and 8) in each sequence would be of lower pitch.

Results

Asynchronies were computed by subtracting the tone onset times from the registered key depression times, both having been measured from sequence onset. Four contiguous episodes of 10 asynchronies each were extracted from each trial, such that each episode began three positions before a perturbation (P − 3) and ended six positions after it (P + 6). The additional asynchronies at the beginning and end of a trial were not analyzed. As is commonly found in synchronization tasks, the taps generally anticipated the tones: The grand average asynchrony (computed from the three pre-P positions in all episodes) was −68 ms, and individual averages ranged from −40 to −93 ms. Because this anticipation tendency was not of particular interest in the present research, the asynchronies in each episode were expressed relative to the asynchrony in Position P. If the average asynchrony is A, then the expected asynchrony in Position P is A − Δt, where Δt is the magnitude of the EOS. In each participant's average data for each Δt condition, the asynchrony in Position P plus Δt was subtracted from all asynchronies in the episode, so that the relative asynchrony at P was exactly −Δt, whereas the expected relative asynchronies in all other positions were zero (assuming absence of a PCR and of systematic phase drift). Any significant deviation from zero in Position P + 1 then represented a PCR, as defined

[1] A MAX patch is a program written in the graphical programming language MAX. Because of a peculiarity of this software, the tempo of the output was about 2.4% faster than specified in the MIDI instructions. The participants' keypresses were registered at a correspondingly slower rate. Throughout this article, all stimulus specifications and results are reported 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 keypresses.

here. If such a response occurred, the relative asynchronies in the positions following P + 1 were expected to return toward zero, due to phase correction of the asynchrony caused by the PCR.

Figure 2 presents the results for the different Δt values. Each function shows relative asynchronies as a function of episode position, averaged across episodes, trials, and participants. The standard error bars represent variability among participants. The upper panel shows the results for the condition in which all tones were of equal pitch (no pitch cue), whereas the lower panel shows the results for the condition in which the perturbed tone had a lower pitch (pitch cue or +p). The relative asynchronies in Position P, which were by definition equal to $-\Delta t$, have been omitted for reasons of graphic layout. The average relative asynchronies immediately preceding an EOS were close to zero, as expected. If participants had been able to ignore the perturbation, the average relative asynchronies should have been close to zero in the following positions as well. However, this was clearly not the case. In six of the eight conditions, the asynchronies in Position P + 1 (i.e., the PCR) deviated significantly from zero, judging from the error bars. The PCR was in the direction of Δt—that is, in the opposite direction of the asynchrony in Position P, as expected.[2] Thus, phase correction evidently could not be avoided, and the subsequent return of the relative asynchronies toward the zero baseline constituted a correction for the asynchrony caused by the unintended PCR. It also seems that negative EOSs (i.e., early tone onsets) elicited a smaller PCR than positive EOSs (i.e., late tone onsets) and were followed by a more rapid return to the baseline.

A repeated measures analysis of variance (ANOVA) was conducted on the PCRs (Position P + 1 only), with the variables of EOS magnitude (2), direction (2), and pitch (2). The signs of the PCRs to negative EOSs were reversed in this analysis, so as to make possible a comparison of the absolute magnitudes of PCRs to positive and negative EOSs. There was a significant main effect of EOS magnitude, $F(1, 7) = 60.6$, $p < .0001$, confirming that the PCRs were larger after 50-ms than after 10-ms EOSs, and also a main effect of direction, $F(1, 7) = 6.4$, $p < .04$, which confirms that the PCRs were larger to positive than to negative EOSs. No other effects reached significance; therefore, it cannot be concluded that the pitch cue had a consistent effect.

A similar ANOVA was conducted on the PCR data after expressing them as percentages of the EOS magnitude—that is, as relative PCRs. Here, the main effect of direction, $F(1, 7) = 7.4$, $p < .04$, and the Magnitude × Pitch interaction, $F(1, 7) = 5.8$, $p < .05$, reached significance, whereas the main effects of magnitude, $F(1, 7) = 5.6$, $p < .06$, and of pitch, $F(1, 7) = 5.5$, $p < .06$, were nearly significant, and the remaining three interactions were at $p < .10$. This complex pattern of results was caused by the results for negative EOSs with pitch cues, in which the PCR to 50-ms shifts amounted to only about 15% of the perturbation magnitude and the PCR to 10-ms shifts amounted to 0% (see Figure 2b). However, in the other three conditions (positive shifts with and without pitch cue and negative shifts without pitch cue), the relative PCR was clearly larger for 10-ms shifts (average = 68%) than for 50-ms shifts (average = 37%).

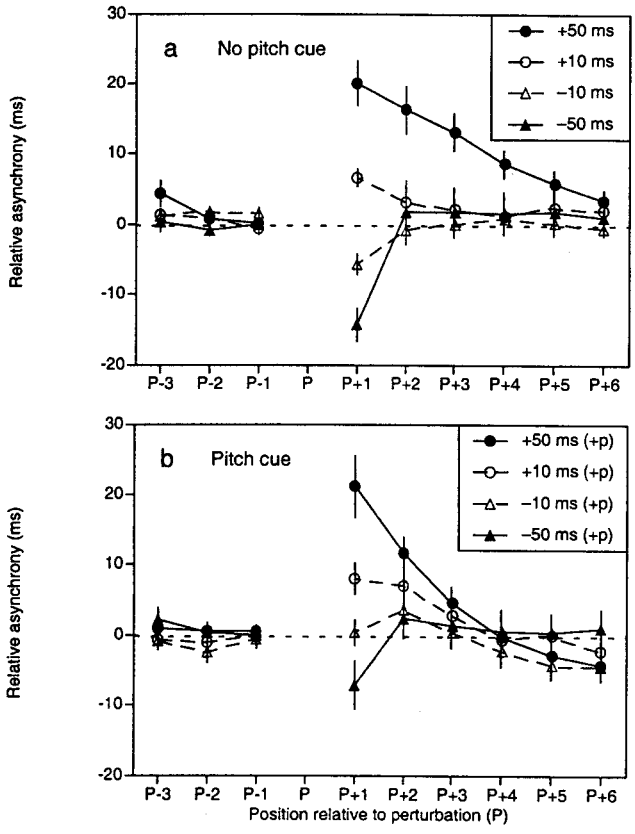

Figure 2. Average compensation functions in Experiment 1 for two absolute magnitudes and two directions of event onset shift, with standard error bars (between-participants variability). The shifted tone either (a) was of the same pitch as the other tones (no pitch cue) or (b) had a lower pitch (pitch cue; +p).

Discussion

The results of Experiment 1 provide a first demonstration that phase correction cannot be suppressed easily. Even though most participants were practiced finger tappers and all tried hard not to react to the EOSs, they did not succeed. No individual participant was able to avoid PCRs altogether. These results thus support the claim that phase correction is an automatic process.

Yet, there was also some preliminary evidence of voluntary control. Models of linear phase correction proposed in the literature (e.g., Mates, 1994a, 1994b; Pressing, 1998; Semjen et al., 2000; Semjen, Vorberg, & Schulze, 1998; Vorberg & Schulze, in press; Vorberg & Wing, 1996) generally predict that the PCR should be a constant percentage of perturbation size, at least for relatively small perturbations, as applied here. The finding of smaller relative PCRs to supraliminal than to subliminal EOSs suggests that participants were able to voluntarily reduce the PCR when they were aware of an EOS. Thus, phase correction may have an obligatory component while at the same time perhaps being amenable to voluntary control. However, this conclusion is tentative and in need of further support. The same can be said with

[2] Following a phase shift, relative asynchronies do not change sign because they are calculated relative to phase-shifted tone onsets. The relative asynchronies following an EOS change sign because they are calculated relative to sequence tones that are not phase shifted.

regard to a possible asymmetry between the PCRs to positive and negative EOSs, of which there was a hint in the data.

A more detailed investigation of the relationship between perturbation size and the PCR was conducted in Experiments 5 and 6. First, however, three experiments are reported that maintained the basic design of Experiment 1 while exploring other factors that might affect the magnitude of the PCR.

Experiment 2

Experiment 2 had two aims: to replicate the first half of Experiment 1 with auditory feedback from the taps and to extend the investigation from synchronized (inphase) to syncopated (antiphase) tapping.

Auditory feedback was considered necessary in the antiphase tapping task, which would have been too difficult with a silent response key, as used in Experiment 1. An inphase tapping condition with auditory feedback was included for comparison. One question of interest was whether the availability of an auditory perceptual reference would reduce the PCRs to EOSs, particularly when the EOS magnitude was supraliminal. In that case, participants might be able to detect their PCRs as irregularities in a self-generated auditory rhythm, and efforts to avoid such irregularities might lead to tighter control over the phase correction process.

This argument applied to an even greater extent in the antiphase tapping task, where the self-generated auditory rhythm meshed with the sequence tones to yield an isochronous rhythm at twice the sequence tempo. Such a faster rhythm might make participants more resistant to EOSs, leading to smaller PCRs. The taps were also further separated in time from the EOSs than in the inphase tapping condition, which also leads to the prediction of smaller PCRs. On the other hand, antiphase tapping is usually considered less stable than inphase tapping (e.g., Kelso, DelColle, & Schöner, 1990), which might lead to the opposite prediction. In an experiment similar to the present one except for the presence of subliminal phase shifts instead of EOSs in the sequences, Repp (2001a, Experiment 2) found no significant difference between inphase and antiphase tapping in tapping variability or effectiveness of phase correction. Therefore, it was expected that the PCRs to EOSs, too, would be similar in the two tapping conditions, at least in the case of subliminal EOSs.

In addition to providing auditory feedback, there was a second change in method relative to Experiment 1 (following Repp, 2001a, Experiment 2): To discourage participants from adopting a strategy of synchronizing the top contacts of the response keys with the tones in the antiphase tapping condition, thus converting it into an inphase tapping condition (see Kelso et al., 1990), participants were instructed to avoid all hard contacts in pressing the key. Thus, the motor activity became a kind of finger–key oscillation, though for convenience it is still referred to as tapping.

Method

Participants. There were 8 participants. Four of them had also served in Experiment 1; they included myself, the younger research assistant, and the 2 undergraduates. The new participants were a research assistant (male, age 41) and 3 undergraduates (female, ages about 19). All participants had some experience in synchronization tasks, but I was the only one with substantial musical training.

Materials. The sequences were those used in the first half of Experiment 1; that is, the shifted tones had the same pitch as the other sequence tones.

Procedure. Participants were instructed to oscillate the response key on the MIDI controller with their index finger without fully depressing or fully releasing the key, thereby avoiding hard contacts. The electronic registration of a key depression occurred about halfway during the downward movement of the key and could not be felt. A digital piano tone of slightly lower pitch (A_7: 3505 Hz vs. C_8: 4168 Hz) and lower intensity (MIDI key velocity of 30 vs. 60) than the sequence tones was made contingent on a key depression, via the MAX patch that controlled the experiment. To make this feedback tone coincide subjectively with the lower turning point of the response key, the tone onset was delayed by 20 ms. (This delay was chosen by me on the basis of my own impressions when piloting the experiment.)

The experiment consisted of two parts requiring inphase tapping and antiphase tapping, respectively. In inphase tapping, participants were asked to make the feedback tones coincide with the sequence tones. In antiphase tapping, the feedback tones were to be placed halfway between the sequence tones. In each part, the same four blocks of sequences were presented in the same order as in Experiment 1. At the beginning of each part, participants were given some practice until they felt comfortable with the task. As in Experiment 1, they were alerted to the presence of EOSs in Blocks 3 and 4 ($\Delta t = \pm 50$ ms), but were urged not to react to them and to keep tapping as regularly as possible. The presence of EOSs in Blocks 1 and 2 ($\Delta t = \pm 10$ ms) was not mentioned.

Results

The grand average asynchrony of inphase tapping (calculated from the three pre-P positions) was −35 ms, with individual averages ranging from −25 to −61 ms. The grand average was only about half the size of the corresponding value in Experiment 1, $t(7) = 4.4$, $p < .004$ (assuming independent samples). The difference may be attributed to the auditory feedback tone, which provided additional perceptual information, and possibly also to the different finger kinematics (cf. Aschersleben & Prinz, 1995; Fraisse, Oléron, & Paillard, 1958; Repp, 2001a). The grand average asynchrony of antiphase tapping was −279 ms. Relative to the midpoints of the 500-ms sequence IOIs, the average antiphase asynchrony thus was −29 ms, which was not significantly different from the average inphase asynchrony, $t(7) = 2.0$, $p < .09$. The 20-ms delay of the feedback tone was not taken into account in these comparisons. The grand average asynchrony between the feedback tones and the sequence tones in inphase tapping was −15 ms, and that between the feedback tones and the IOI midpoints in antiphase tapping was −9 ms.

Relative asynchronies were computed as in Experiment 1. The average results are shown in Figure 3. The upper panel represents inphase tapping; the lower panel represents antiphase tapping. In the latter condition, Position P in the series of taps was defined as the tap that preceded an EOS. Thus, the PCR (the tap in Position P + 1) followed the EOS by about 250 ms in antiphase tapping, as compared with about 500 ms in the inphase tapping condition. Despite this difference in time lag, the response patterns in the two conditions were quite similar. There was also less of an asymmetry between the PCRs to positive and negative EOSs than in Experiment 1, and the data were generally less variable, probably due to the auditory feedback. Some differences between the (blocked) 10-ms and 50-ms EOS conditions in the later positions seem to be due to phase drift, which is not of particular interest here.

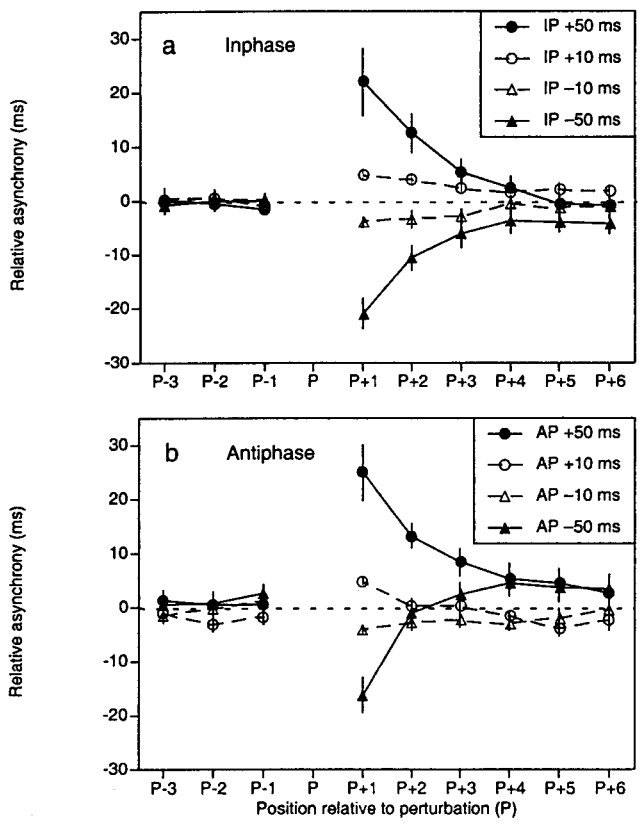

Figure 3. Average compensation functions in Experiment 2 for two absolute magnitudes and two directions of event onset shift (EOS), with standard error bars (between-participants variability). (a) Inphase (IP) tapping. (b) Antiphase (AP) tapping. In antiphase tapping, the EOS occurred between Positions P and P + 1.

A repeated measures ANOVA was conducted on the PCRs (Position P + 1), with the variables of condition (inphase vs. antiphase), EOS magnitude (10 vs. 50 ms), and direction (positive vs. negative); the sign of the data for negative EOSs was reversed. There was only a significant main effect of EOS magnitude, $F(1, 7) = 21.0$, $p < .003$. The PCRs were larger for 50-ms than for 10-ms EOSs, but they did not show any significant asymmetry (though there was a tendency toward smaller PCRs to negative EOSs in the antiphase condition) and were not significantly different between the tapping conditions. An analogous ANOVA on the relative PCRs did not yield any significant effects. In particular, the average relative PCRs were similar for subliminal and supraliminal EOSs (45% vs. 42%, respectively).

Discussion

The results of the inphase condition replicate the finding of Experiment 1 that a PCR to an EOS cannot be avoided. All participants produced PCRs even in the presence of auditory feedback. The relative PCRs obtained were smaller than those for subliminal EOSs in Experiment 1, but about as large as those for supraliminal EOSs in that experiment. The absence of any significant difference between the PCRs in inphase and antiphase tapping is consistent with previous findings for phase correction following phase shifts (Repp, 2001a), although several conflicting tendencies may have conspired to generate this result.

Experiment 2 did not replicate two tendencies observed in Experiment 1, namely that PCRs were larger to positive than to negative EOSs and that relative PCRs were larger for subliminal than for supraliminal EOSs. The failure to replicate the latter result raises some doubts about participants' ability to partially suppress PCRs to supraliminal EOSs. However, these doubts were laid to rest in Experiments 5 and 6 (see below).

Experiment 3

Experiment 3 investigated to what extent an isochronous reference pulse might aid participants in reducing or suppressing the unintended PCR. Participants were presented with two interleaved sequences of tones of different pitch (alternating in antiphase) and were required to tap in synchrony with one of these sequences, the target sequence. EOSs occurred either in the target (inphase) sequence or in the distractor (antiphase) sequence. If participants were able to focus on the target sequence and ignore the distractor sequence, then EOSs in the target sequence should elicit PCRs of about the same magnitude as in Experiments 1 and 2, whereas EOSs in the distractor sequence should have no effect. If selective attention failed, then, given the finding of equally large PCRs in inphase and antiphase tapping (Experiment 2), PCRs in both conditions should be about half the size of those in previous experiments. In other words, the presence of an EOS would compete with the absence of an EOS, and a compromise PCR should result. Thus, it was hypothesized that the relative magnitudes of the PCRs to target and distractor EOSs might serve as a measure of auditory selective attention.

Method

Participants. The 8 participants were the same as in Experiment 2.

Materials. In most respects, the sequences and blocks of trials were like those in Experiments 1 (first half) and 2. However, in the first part of the experiment (inphase EOSs), an isochronous distractor sequence, composed of tones that were three semitones lower in pitch (A_7: 3505 Hz) and of the same nominal intensity (MIDI velocity of 60) as the target tones (C_8: 4168 Hz), was interleaved with the target sequence containing the EOSs. In the second part of the experiment (antiphase EOSs), the target sequence was isochronous and the lower-pitched distractor sequence contained the EOSs. Both component sequences had a baseline IOI of 500 ms and were in exact antiphase (i.e., 250 ms apart), except where an EOS occurred. Each trial started with a high-pitched (target) tone. In view of the small pitch difference between the two interleaved sequences, no significant pitch-based asymmetries were expected; therefore, only the high-pitched sequence was used as a target for synchronization.

Procedure. The tapping regime was the same as in Experiment 1; that is, the response key was quiet and had to be depressed and released fully. Participants started tapping with the second high-pitched tone on each trial and were urged not to react to any perturbations but to keep tapping as regularly as possible. The sequence of blocks within the two conditions was the same as in the preceding experiments.

Results

The grand average asynchrony (computed from the three pre-P positions in all episodes) was −39 ms, with individual averages ranging from −15 to −67 ms. The average value was similar to the

average asynchrony in Experiment 2 and significantly smaller than that in Experiment 1, $t(7) = 4.4$, $p < .003$ (assuming independent samples), even though the tapping style (no auditory feedback and full key depression and release) was the same as in Experiment 1. This reduction in the anticipation tendency thus was most likely caused by the presence of the distractor sequence.

The average relative asynchronies are shown in Figure 4. The upper panel shows the condition in which the EOSs were in the target sequence (inphase), and the lower panel shows the condition in which the EOSs were in the distractor sequence (antiphase). In the latter condition, the EOS occurred between target positions P and P + 1. It is evident that systematic PCRs occurred in both conditions but that they were smaller than in the preceding experiments. (Note the different scale on the *y*-axes.) As in Experiment 2, the results were quite similar for the inphase and antiphase conditions. There was a hint of an asymmetry between the PCRs to positive and negative EOSs in only the inphase condition.

A repeated measures ANOVA was conducted on the PCRs, with the variables of condition (inphase vs. antiphase), EOS magnitude (10 vs. 50 ms), and direction (positive vs. negative); the sign of the data for negative EOSs was reversed. There was only a significant main effect of EOS magnitude, $F(1, 7) = 32.2$, $p < .0009$. After converting the PCRs into percentages of EOS magnitude, the main effect of magnitude fell short of significance, $F(1, 7) = 4.9$, $p < .07$. Although the average relative PCR was larger for 10-ms EOSs (30%) than for 50-ms EOSs (18%), only 5 of the 8 participants showed a clear difference in this direction. Thus, as in Experiment 2, there was no strong evidence of partial suppression of the PCR to supraliminal perturbations.

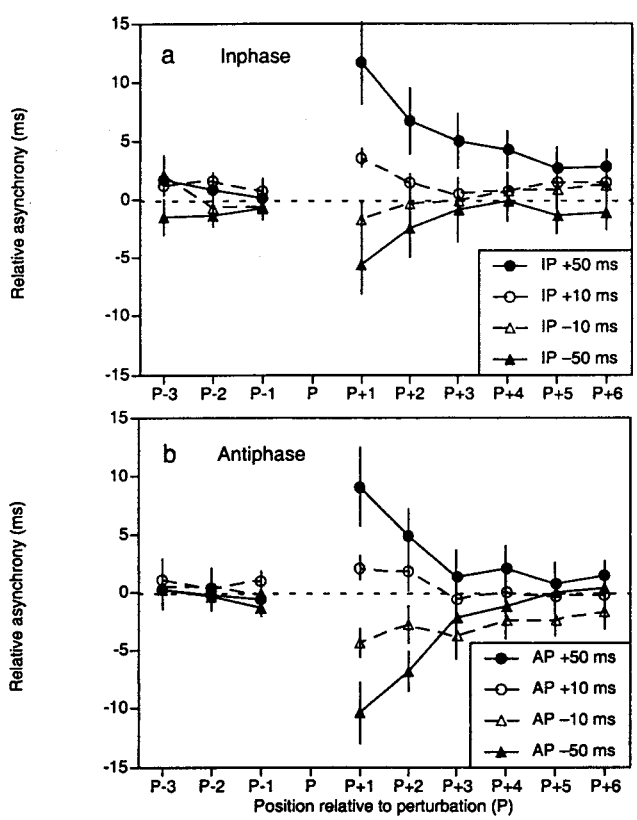

Figure 4. Average compensation functions in Experiment 3 for two absolute magnitudes and two directions of event onset shift (EOS), with standard error bars (between-participants variability). (a) Perturbations in the target (inphase; IP) sequence. (b) Perturbations in the distractor (antiphase; AP) sequence. In the latter condition, the EOS occurred between Positions P and P + 1.

The relative PCR data of Experiments 2 and 3 were entered into a joint ANOVA with the additional repeated measures factor of experiment (2). The main effect of experiment, $F(1, 7) = 24.6$, $p < .003$, was the only significant effect in this analysis, which confirmed that the average relative PCR was smaller in Experiment 3 (24%) than in Experiment 2 (44%). Thus, the presence of an isochronous sequence, either as distractor or as target, reduced the PCR, and it did so equally for subliminal and supraliminal EOSs. The Experiment × Magnitude interaction did not even approach significance, $F(1, 7) = 0.6$. Only the main effect of magnitude was nearly significant, $F(1, 7) = 5.2$, $p < .06$, suggesting that some participants were able to suppress their PCRs to supraliminal EOSs.

Discussion

The reduction in the anticipation tendency relative to Experiment 1 suggests that participants perceptually integrated the target and distractor sequences into a single sequence having twice the tempo of the individual sequences. It is known that the anticipation tendency decreases as the sequence tempo increases (e.g., Engström, Kelso, & Holroyd, 1996; Mates et al., 1994; Peters, 1989), but this was observed in studies in which the tempo of the synchronized tapping increased as well. Here, the tempo of the tapping was the same as in Experiment 1, so that participants effectively tapped with every other tone of a sequence having IOIs of 250 ms. Such an effect of sequence tempo alone on the average asynchrony does not seem to have been demonstrated previously, although it may be related to Wohlschläger and Koch's (2000) recent finding that insertion of additional (randomly timed) tones into sequence IOIs reduces the anticipation tendency.

The PCR results are likewise consistent with the hypothesis that participants integrated the target and distractor sequences into a compound rhythm (see also Bregman, 1990; Brochard et al., 1999). This is perhaps not surprising because the two interleaved sequences were only three semitones apart in pitch, which corresponds to about 1.4 equivalent rectangular bandwidths (ERBs; Glasberg & Moore, 1990). Although Brochard et al. (1999) determined that a separation of 1 ERB was sufficient to enable listeners to attend selectively to one of two simultaneous tone sequences, this result was obtained with sequences that had continuously changing phase relationships. The fact that the present sequences were in strict antiphase (i.e., they formed an isochronous rhythm with a two-level metrical structure) may have favored their perceptual integration into a compound rhythm.

There is an alternative interpretation of the results, however. Rather than reflecting participants' inability to attend selectively to the target sequence and to ignore the distractor sequence, the equally large PCRs in the inphase and antiphase conditions may indicate that phase correction is insensitive to selective attention and auditory organization. The main hypothesis underlying this study is that phase correction is an automatic process that occurs at a relatively early level in temporal processing. It is possible that

this process is based on only the registration of event onsets and therefore is not sensitive to factors such as attentional focus and pitch distance that bear on perceptual stream segregation (Bregman, 1990). Experiment 4 pursued this hypothesis in a preliminary way by substantially increasing the pitch distance between the target and distractor sequences.

Experiment 4

Experiment 4 was similar to Experiment 3, but the interleaved sequences were separated by 20 rather than only 3 semitones. If the phase correction process is sensitive to pitch separation and auditory stream segregation, then the inphase condition (i.e., when the EOSs are in the target sequence) now should exhibit a larger PCR, similar to that observed in tapping to a single sequence (as in Experiments 1 and 2), whereas the antiphase condition (i.e., when the EOSs are in the distractor sequence) should show little or no evidence of a PCR. Alternatively, if phase correction is independent of factors that affect auditory stream segregation, the results should replicate those of Experiment 3. In view of possible pitch-related asymmetries due to the large pitch difference, either of the two interleaved sequences served as a target for synchronization in Experiment 4.

Method

Participants. Six of the 8 participants were the same as in Experiments 2 and 3; they included myself, the young research assistant, and 4 undergraduates. The 2 additional participants were a postdoctoral researcher, who also participated in Experiment 1, and a new research assistant (female, age 31). Only the postdoctoral researcher and I had substantial musical training, but all participants either had considerable experience with synchronization tasks or, in the case of the newcomer, were able to tap right away with relatively low variability.

Materials. The sequences and trial blocks were similar to those of Experiment 3, except that the tones of the lower-pitch sequence had a pitch (E_6: 1320 Hz) 20 semitones below that of the higher-pitch sequence (C_8: 4168 Hz). Because the lower tones sounded louder than the high tones when played at the same MIDI key velocity of 60, their velocity was reduced to 50 (about −3 dB; see Repp, 1997, Figure 1), which resulted in approximately equal loudness (informal judgment by me and the postdoctoral researcher). By deleting the first (high) tone in the sequences, a second set of sequences was created in which the first tone was low.

Procedure. The procedure was the same as in Experiment 3, but a more elaborate, counterbalanced design was used across two sessions, each of which comprised eight blocks of 10 trials each. One session used the sequences starting with a high tone, the other session used those starting with a low tone. During the first four blocks in each session, the EOSs were in one component sequence (either high or low), and during the last four blocks, they were in the other component sequence. Within each group of four blocks, the first two blocks always contained 10-ms EOSs, and the second two contained 50-ms EOSs. The target sequence, and thus the experimental condition (inphase vs. antiphase EOSs), alternated from block to block. The pitch of the target sequence (high or low) was announced by the experimenter at the beginning of each block and was also displayed on the computer monitor. Participants were asked to begin tapping with the second tone of the target sequence.

Results

The grand average asynchrony (computed from the three pre-P positions in all episodes) was −50 ms, with individual averages ranging from −25 to −100 ms. The average value was smaller (i.e., less negative) than the average asynchrony in Experiment 1 (−68 ms) but larger than that for interleaved sequences of similar pitch in Experiment 3 (−39 ms), although neither difference reached significance. Of the 6 individuals who participated in both Experiments 3 and 4, 3 produced substantially larger asynchronies in Experiment 4, but the other 3 showed little difference. Thus, if the anticipation tendency can be taken as an index of segregation, it suggests that some, but not all, participants segregated the sequences more when they were more different in pitch.

The average relative asynchronies are displayed in Figure 5, which is analogous to Figure 4. Again, the upper panel represents the condition in which the EOSs were in the target sequence (inphase), and the lower panel shows the condition in which the EOSs were in the distractor sequence (antiphase). In the latter condition, the perturbation occurred between target positions P and P + 1. The results were very similar to those of Experiment 3. They did not confirm the prediction that stream segregation would increase the PCRs to inphase EOSs and decrease those to antiphase EOSs.

A repeated measures ANOVA was conducted on the PCRs (Position P + 1), with the variables of EOS pitch (high vs. low), target pitch (high vs. low), EOS magnitude (10 vs. 50 ms),

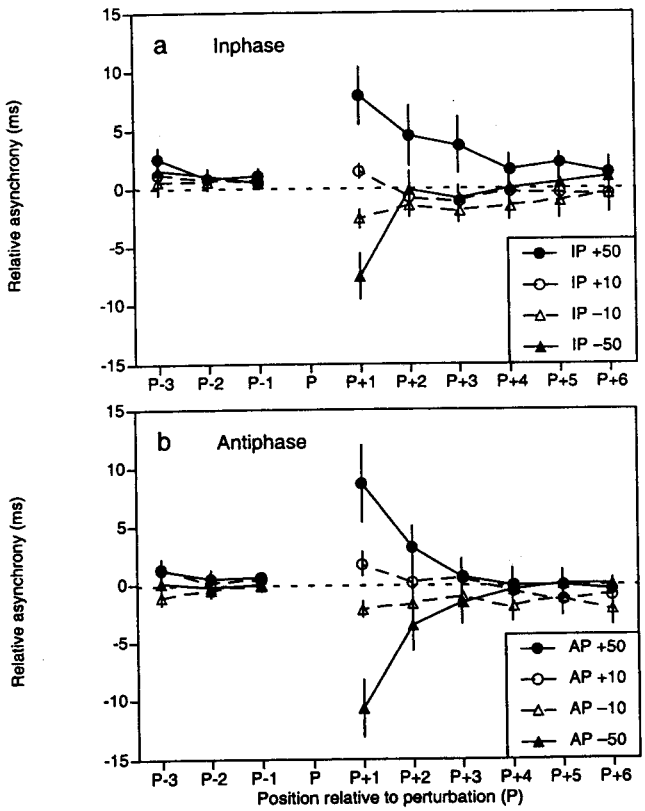

Figure 5. Average compensation functions in Experiment 4 for two absolute magnitudes and two directions of event onset shift (EOS), with standard error bars (between-participants variability). (a) Perturbations in the target (inphase; IP) sequence. (b) Perturbations in the distractor (antiphase; AP) sequence. In the latter condition, the EOS occurred between Positions P and P + 1.

direction (positive vs. negative), and starting pitch of the sequence (high vs. low). The sign of the data for negative EOSs was reversed. In this factorial design, the EOS Pitch × Target Pitch interaction represented the main effect of condition (inphase vs. antiphase), which was not significant. There was a significant main effect of EOS magnitude, $F(1, 7) = 37.1$, $p < .0006$. The only other significant effect was the Starting Pitch × EOS Pitch × Magnitude interaction, $F(1, 7) = 11.9$, $p < .02$, which may reflect a subtle effect of metrical organization (related to starting pitch) but will not be discussed further here. After converting the PCRs into percentages of EOS magnitude, the main effect of magnitude was no longer significant. The average relative PCR was 20% of 10-ms and 17% of 50-ms perturbations, which revealed no evidence of suppression of the PCR to the larger perturbations. The data were rearranged and entered into a combined ANOVA with the relative PCR data from Experiment 3, including only the 6 participants who participated in both experiments. The variables in this analysis were experiment, condition (inphase vs. antiphase), EOS magnitude, and direction. No significant effects emerged.

Discussion

The absence of any effect of the pitch distance manipulation on the average PCR suggests that the phase correction process is independent of auditory stream segregation. It must be acknowledged that, because of the moderate tempo of the present sequences, stream segregation was by no means obligatory, despite the large pitch difference (see Bregman, 1990). Nevertheless, the task requirement of synchronizing with the target sequence directed attention to that sequence, and the large pitch separation should have made the distractor sequence easier to ignore. In a temporal discrimination task, Brochard et al. (1999) obtained results indicative of stream segregation with interleaved sequences of similarly moderate tempo. Indeed, their data suggest that the three-semitone pitch difference used in Experiment 3 may have been already sufficient to segregate the two sequences. If so, then the results of both Experiments 3 and 4 suggest that the PCR is unaffected by stream segregation.

Alternatively, it may be that the sequences of Experiment 4 were still perceptually integrated into a single rhythmic structure, despite the large pitch difference. This seems contrary to the results of Brochard et al. (1999), but, as already mentioned, they did not use sequences that formed a composite rhythm. The relationship between phase correction and stream segregation is a theoretically interesting issue that clearly requires further research, especially with sequences that induce obligatory segregation. As far as these preliminary results go, however, they are consistent with the hypothesis that phase correction is based on the automatic registration of event onsets and is independent of auditory scene analysis and selective attention.

Experiment 5

Experiment 5 returned to the basic task of tapping in synchrony with a single sequence containing EOSs and investigated in more detail the relationship between EOS magnitude and the size of the unintended PCR. The results of Experiment 1 suggested that participants are able to reduce their relative PCRs to 50-ms EOSs, compared with their relative PCRs to 10-ms EOSs, perhaps as a consequence of being aware of the larger EOSs. However, Experiments 2–4 provided little additional evidence in favor of this conclusion. One problem with these experiments is that they used only two absolute EOS magnitudes, the larger of which was perhaps not large enough, even though it was clearly detectable. Experiment 5 used a much wider range of magnitudes, extending up to half the IOI duration.

As outlined in the introduction, the relationship between PCR magnitude and EOS magnitude could in theory take one of four different forms: (a) It could be linear, as predicted by the linear phase correction model of Mates (1994a), Pressing (1998), and Vorberg and Wing (1996). This is perhaps a naive prediction, because the model was not intended to account for responses to large perturbations (but see Semjen et al., 1998). The prediction can be qualified as stating that the unintended PCRs to EOSs should follow the same function (linear or not) as the intended PCRs to phase shifts. (The form of the latter function was investigated in Experiment 6.) Such a result would indicate that participants have no control whatsoever over their PCRs. This was indeed expected to hold for the PCRs to subliminal EOSs. For supraliminal EOSs, however, three other possibilities were envisioned. (b) The slope of the function might decrease above a certain EOS magnitude, which perhaps coincides with the detection threshold. If it were the case that this slope also decreases for PCRs to phase shifts, then the prediction is that the slope for PCRs to EOSs should decrease even more. This would indicate that participants can voluntarily adjust a parameter that controls their phase correction process. (c) The slope of the PCR function may reach zero beyond a certain EOS magnitude, which may coincide with the point of asymptotic detection performance. This would suggest that an absolute limit can be imposed on the PCR by some factor that is external to the phase correction process. (d) Finally, the PCR may disappear for large EOSs. This would suggest that complete suppression of the PCR is possible when the perturbation is large enough.

So that the PCR results could be compared to detection thresholds for EOSs, participants were required to report after each sequence whether they had perceived an EOS and what its direction was. On the basis of earlier findings in the literature (summarized by Friberg & Sundberg, 1995), the detection thresholds were expected to be near ±20 ms (for 500-ms baseline IOIs). So that the threshold region could be sampled more accurately than the other regions of EOS magnitude, the EOS values were divided into two subranges, one straddling the expected detection threshold and being closely spaced, and the other extending to longer values and varying in larger increments.

Experiment 5 also reinvestigated a possible asymmetry in the PCRs to positive and negative EOSs, which had appeared in Experiment 1 but had vanished in subsequent experiments. In that connection, it should be noted that PCRs to phase shifts generally show no asymmetry (Repp, 2000, 2001a). Confirmation of such an asymmetry in PCRs to EOSs would suggest that it arises outside the phase correction process itself. The detection threshold for phase shifts, however, tends to be lower for positive than for negative changes (Repp, 2000).

Method

Participants. The 8 participants were the same as in Experiments 2 and 3.

Materials. The sequences in this study were from 13 to 17 tones long, and each contained only a single EOS. The baseline IOI was 500 ms. Each sequence consisted of high-pitched (C_8: 4168 Hz) digital piano tones. The EOS occurred in the 8th, 9th, 10th, 11th, or 12th position. The sequence length varied with the position of the EOS, such that five unperturbed tones always followed the shifted tone. There were two ranges of EOS magnitudes. Small shifts, which were expected to span the detection threshold, were 10, 15, 20, 25, and 30 ms in either direction. Large shifts, which were expected to be easily detectable, were 50, 100, 150, 200, and 250 ms in either direction. For each range, there were 50 different sequences (5 positions × 2 directions × 5 magnitudes). Each set of 50 sequences was randomized and divided into two blocks.

Procedure. Participants read printed instructions that explained the concept of an EOS with diagrams. Their subsequent task was to tap in synchrony with each sequence, starting on the second tone, not to react to any shifted tones, and to report afterward whether they had heard an EOS in the sequence as well as the direction of that shift. They were informed that all sequences contained EOSs but were asked to report their perceptual experience and not to guess. The detection response was made on the computer keyboard by pressing the down arrow (↓) key if no irregularity was perceived, the left arrow (←) key if an early tone onset (negative EOS) was detected, and the right arrow (→) key if a late tone onset (positive EOS) was detected.[3]

The tapping was carried out on the quiet MIDI controller, which was held on the participant's lap, as in Experiments 1, 3, and 4. The detection response on the computer keyboard caused the trial number on the computer monitor to be incremented 2 s later and the next sequence to start after a further delay of 2 s. Participants first received a few practice sequences containing large EOSs, followed by a few sequences containing small EOSs. Then eight blocks of 25 sequences each were presented. Blocks 1, 2, 5, and 6 contained small EOSs; Blocks 3, 4, 7, and 8 contained large EOSs.

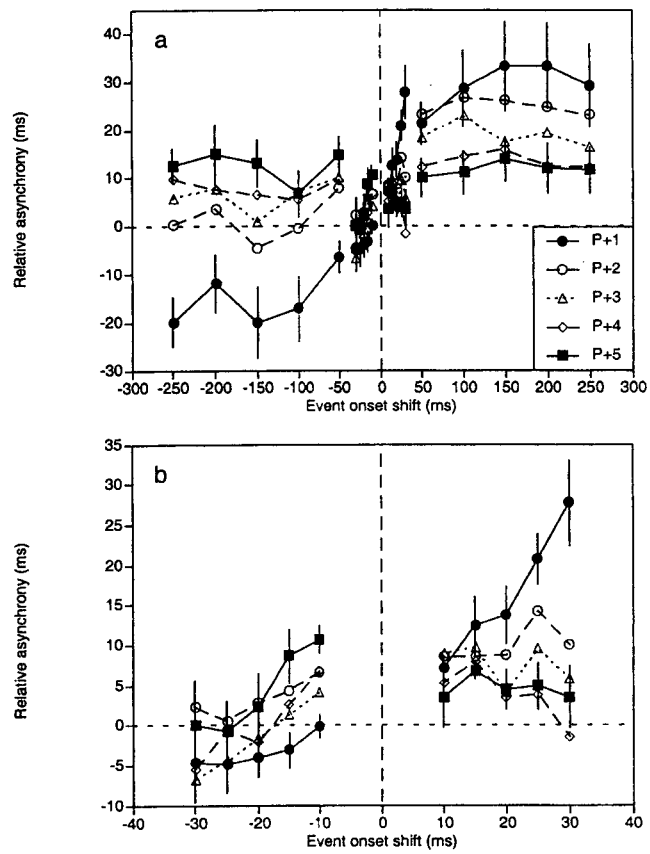

Figure 6. Average relative asynchronies for five taps following event onset shifts of various magnitudes and directions in Experiment 5, with standard errors (between-participants variability). (a) Whole range. (b) Narrow range only.

Results

The grand average asynchrony, computed from the three pre-P positions, was −60 ms, with individual averages ranging from −21 to −91 ms. These values were similar to those observed in Experiment 1. Relative asynchronies were again computed by subtracting the asynchrony in Position P plus Δt from all other asynchronies.

Figure 6 shows the average relative asynchronies in the five positions following P as a function of EOS magnitude. (Note the different format compared with earlier figures, in which relative asynchronies for different EOS magnitudes were plotted as a function of position.) Figure 6a plots the results for all EOSs, whereas Figure 6b concentrates on the results for small EOSs, which are difficult to discern in Figure 6a. Standard errors are shown for only Positions P + 1 and P + 5, to avoid clutter. The results in Figure 6a show that the PCRs (Position P + 1) reached an asymptote as EOS magnitude increased. The asymptotic PCR was about −20 ms for negative EOSs and about 30 ms for positive EOSs, and it was reached at EOSs of about ±100 ms, or perhaps earlier. Thus, there was an asymmetry in the asymptotic PCRs, but between-participants variability was large. The PCRs to small EOSs (Figure 6b) showed a more pronounced asymmetry: Whereas PCRs to positive EOSs increased steeply in a roughly linear fashion (slope of 0.84, regression line forced through zero), those to negative EOSs were much smaller and increased only slightly with EOS magnitude (slope of 0.17). There was also evidence of phase drift: In the blocks containing large EOSs, the taps in Position P + 5 were delayed by about 10 ms relative to the zero baseline. This drift was less pronounced in the blocks containing small EOSs, and a curious dependency on EOS magnitude persisted in the taps following negative EOSs, suggesting an EOS-dependent phase shift.

The PCR data (Position P + 1) for small EOSs were entered into a repeated measures ANOVA with the variables of EOS magnitude (5) and direction (2). As in previous analyses, the sign of the PCRs following negative EOSs was reversed. The main effect of

[3] The first 6 participants were also instructed to press the up arrow (↑) key if they thought they had heard a shift but could not tell its direction. It was expected that this option would be used only rarely. However, 3 of the undergraduate participants used the up arrow (↑) key much more frequently than the down arrow (↓) key when the perturbations were very small, perhaps as a consequence of having been told that all trials contained an EOS. Because the distribution of these up arrow key responses was similar to that of other participants' down arrow key responses, up arrow key and down arrow key responses were combined into a single *no change* category. The last 2 participants were not given the up arrow key option.

EOS magnitude was highly significant, $F(4, 28) = 13.2$, $p < .0001$, indicating that the PCRs increased with perturbation size. The main effect of direction was only marginally significant, $F(1, 7) = 5.7$, $p < .05$. Although all 8 participants showed larger PCRs to positive than to negative EOSs, the size of the difference varied greatly. The Direction × Magnitude interaction was also significant, $F(4, 28) = 3.9$, $p < .02$, because the increase of the PCR with EOS magnitude was steeper on the positive than on the negative side (see Figure 6b). A similar ANOVA on the PCRs to large EOSs yielded only a significant main effect of magnitude, $F(4, 28) = 3.6$, $p < .02$, mainly because of smaller PCRs to 50-ms EOSs than to EOSs of 100 ms or more (see Figure 6a). The apparently smaller PCRs to large negative than to large positive EOSs were not reliable as a group result; this tendency was due to only 3 participants, two of whom did not show any PCRs at all to large negative EOSs. Thus, there were considerable individual differences in this task.

The average percentages of the detection responses are shown in Figure 7. Figure 7a shows the responses to all EOS magnitudes, whereas Figure 7b shows the results for small EOSs in more detail. As expected, the percentage of *no change* responses decreased, whereas the percentages of correct responses increased as EOS magnitude increased. There were some incorrect responses (early tone onsets being identified as late and vice versa), more on the negative than on the positive side. The average detection thresholds, in terms of the 50% crossovers of the correct response functions, were −20 ms for negative shifts and 18 ms for positive shifts. Although this difference was small, positive EOSs were detected and identified more accurately overall. A repeated measures ANOVA on the percent correct responses for small shifts yielded a significant main effect of direction, $F(1, 7) = 7.3$, $p < .04$, which confirms the asymmetry visible in Figure 7b.

Did the PCRs depend on awareness of an EOS? Clearly, the EOS magnitudes at which the average PCRs reached asymptote (about ±100 ms) did not coincide with the average 50% detection thresholds (near ±20 ms). However, they did approximately coincide with the asymptotes of the detection functions (see Figure 7a). Therefore, it could be argued that the average PCRs represent a mixture of two kinds of response, one to undetected EOSs (presumably increasing with EOS magnitude) and the other to detected EOSs (presumably responsible for the PCR asymptote and hence less dependent on EOS magnitude). This possibility was examined by reanalyzing the PCRs to small EOSs separately for those trials on which the detection response was positive and correct (*early* for negative EOSs, *late* for positive EOSs) and for those on which the response was negative (*no change*). Trials receiving incorrect positive responses were excluded. Figure 8 shows the results.[4] For negative EOSs, there was no consistent difference between the PCRs to detected and undetected shifts. For positive EOSs, there was no difference for shifts of up to 20 ms, but for EOSs of 25 and 30 ms, the PCR was larger to detected than to undetected shifts, judging by the nonoverlapping standard error bars. Although this difference suggests a possible role of awareness, its direction is puzzling, because awareness of an EOS was expected to reduce, not increase, the unintended PCR. Because the phase correction process itself seems to be independent of awareness of a perturbation (Repp, 2000), perhaps a more plausible explanation of the difference in Figure 8 is that positive detection responses were sometimes based on awareness of a large PCR rather than on perception of the EOS that gave rise to it.

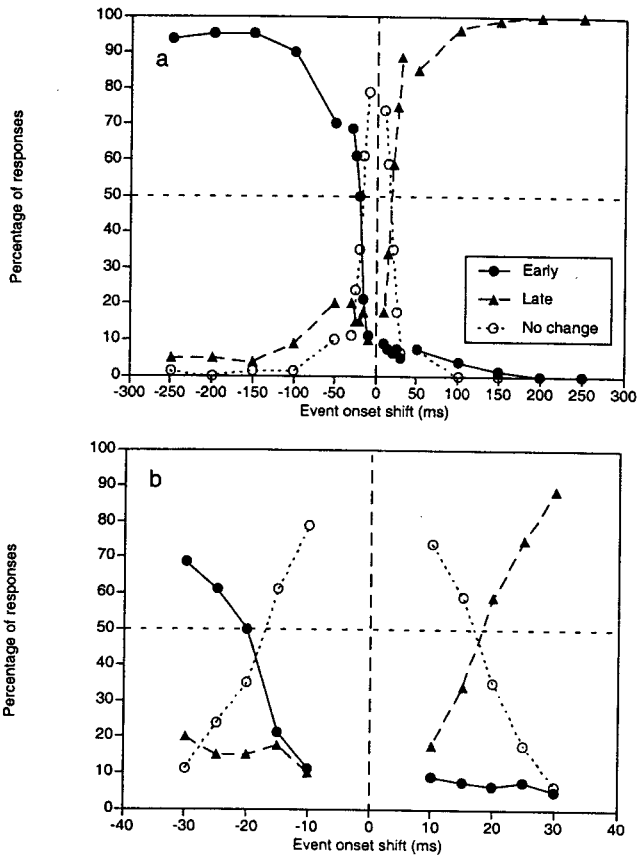

Figure 7. Average percentages of detection responses (*early, late,* or *no change*) as a function of event onset shift magnitude in Experiment 5. (a) Whole range. (b) Narrow range only.

Discussion

The results of Experiment 5 demonstrate that the average PCR increases with EOS magnitude in an approximately linear fashion and then reaches an asymptote at a relatively small magnitude.[5] This indicates that participants have control over their PCRs to large EOSs. This control does not seem to represent a parameter adjustment in the phase correction process itself; if it did, PCR magnitude should have continued to increase, albeit with a shal-

[4] These data were analyzed in two ways. In one analysis, the results of which are shown in Figure 8, separate means were computed for the two types of trial for each participant, and these means were then averaged to yield a grand mean. In the other analysis, a grand mean asynchrony was computed across all trials of a certain category by combining the data of all participants (effectively, a weighted mean of participant averages). The results were similar.

[5] Admittedly, the results are stronger with regard to the PCR asymptote than with regard to a linear dependency of PCRs on small EOSs. However, clear support for a linear relationship has been obtained in recent experiments with both auditory and visual sequences (Repp & Penel, in press).

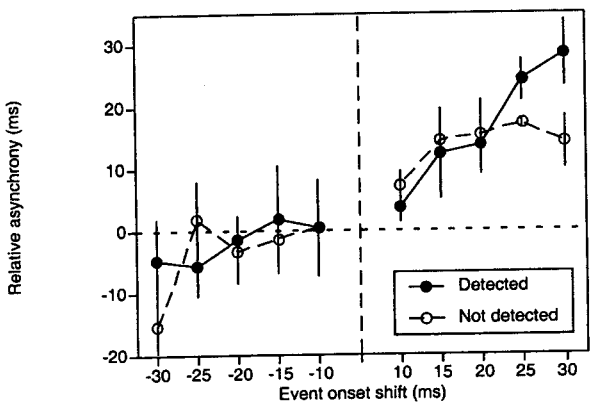

Figure 8. Average phase correction responses to small event onset shifts in Experiment 5, contingent on whether or not the perturbation had been detected, with standard errors (across participants).

lower slope. It is unclear whether awareness of large EOSs played a role, and even if it did, awareness alone cannot explain the asymptotic behavior of the PCR function. The following tentative explanation is suggested instead: The asymptotic values of the PCR function may represent participants' more or less successful efforts to keep the PCRs below the detection thresholds for temporal irregularities in their own tapping. These thresholds were likely to be higher than those for the perception of EOSs, because the taps were both silent and inherently variable. It is unclear whether any participants were aware of their PCRs, but certainly there were some (such as I myself) who thought they were quite successful in not reacting to the EOSs. The nature of the control process that keeps PCRs below this irregularity detection threshold remains to be clarified.

Experiment 5 also revealed a striking asymmetry in the PCRs to positive and negative EOSs. Even though negative EOSs are more difficult to detect, they elicited smaller PCRs, which suggests that control of PCRs to negative EOSs is possible even without awareness of these EOSs. Because ordinary phase correction in response to phase shifts does not normally show an asymmetry (Repp, 2000; see also Experiment 6 below), the asymmetry in the PCRs to small EOSs may be located in the control process that is also responsible for the PCR asymptotes.

One difficulty in interpreting the results of Experiment 5 is the absence of comparable data in a situation in which the PCRs are intended. So that it could be confidently concluded that the unintended PCRs to large EOSs were reduced and under voluntary control, it was necessary to demonstrate that they were smaller than intended PCRs to similarly large phase shifts. This was the purpose of Experiment 6.

Experiment 6

Experiment 6 was identical in design to Experiment 5. The only differences were that phase shifts occurred instead of EOSs, and participants were instructed to stay in synchrony with the sequences. Because EOSs and phase shifts are initially identical (see Figure 1), differences in the PCRs (Position P + 1) to EOSs and to phase shifts could only be due to participant's intentions and expectations. The phase correction following the PCR is necessarily different for EOSs and phase shifts, but the focus here was on the PCR and its dependence on phase shift magnitude. It was expected that PCRs to large phase shifts would be considerably larger than PCRs to large EOSs. However, PCRs were expected to be similar for subliminal phase shifts and EOSs.

Experiment 6 also provided an opportunity to test the generality of the linear phase correction model proposed by several authors (Mates, 1994a, 1994b; Pressing, 1998; Semjen et al., 1998, 2000; Vorberg & Wing, 1996). In its simplest form, this model predicts that the average PCR is a constant proportion of the most recent relative asynchrony. This implies a linear change in PCR magnitude as a function of phase shift magnitude. Two possible nonlinearities in this relationship have been considered previously. One such nonlinearity might occur in the vicinity of zero, because of a detection threshold below which there would not be any phase correction. Repp (2000) examined this hypothesis and found no evidence in support of it. The other possible nonlinearity may arise at larger perturbations, because of inherent dynamic system properties (Engbert et al., 1997; Large & Jones, 1999; Pressing, 1999). A detailed discussion of dynamic systems approaches to rhythmic coordination is beyond the scope of this article; these models generally assume a nonlinear (sinusoidal or sigmoidal) error correction function, such that the slope of the PCR function would be steepest around zero and become shallower as the phase shift magnitude increases. Whether such a function adequately characterizes the data is an empirical question.

The linear phase correction model accounts well for error correction in synchronization with isochronous (or nearly isochronous) sequences, in which the asynchronies arise mainly from variability in tap timing and generally stay within a range of ±50 ms around the mean asynchrony. The model has rarely been tested with a wide range of perturbations. Only Semjen et al. (1998) introduced large phase shifts and found the results to be generally consistent with a linear phase correction model, as long as alternative correction strategies for the same perturbation were taken into account. However, Semjen et al. used only a few phase shift magnitudes and an unusual paradigm in which the tone sequence began after tapping had started. Experiment 6 provided a more straightforward test of the linearity assumption.

All extant phase correction models seem to assume symmetric responses to positive and negative perturbations. Repp (2000, 2001a), in experiments using small phase shifts, generally did not find any significant asymmetries. However, there was a clear asymmetry in one experiment (Repp, 2000, Experiment 5) that used phase shifts in the range of ±10 to ±30 ms (corresponding to the range of small phase shifts in the present experiment): Phase correction for positive phase shifts was almost immediate (i.e., the PCR was near 100%), whereas that for negative phase shifts was slower. This asymmetry is consistent with the one observed in Experiment 5 (see Figure 6), because a weaker PCR may be easier to suppress, but it remained to be seen whether this exceptional asymmetry for phase shifts is replicable.

Method

Participants. Six of the 8 participants had participated in Experiment 5. They included myself, the young research assistant, and 4 undergraduates. All of them had considerable task experience, but only I had substantial musical training. The new participants were a visiting scholar (female, age 26) with a few years of musical training and a graduate student violinist

(male, age 27). Both had previously participated in only Experiment 7, which preceded Experiment 6 chronologically.

Materials. The materials were identical to those of Experiment 5, except that, instead of a single shifted tone (i.e., two changed IOIs), they contained a single changed IOI, the one preceding the first shifted tone (P). After that phase shift, the sequence continued at the baseline IOI of 500 ms.

Procedure. The order of conditions and the procedures were the same as in Experiment 5, except that participants were informed about the phase shifts and were told to stay in synchrony with the tones at all times. Participants again indicated after each sequence, by pressing a key on the computer keyboard, whether they had detected an irregularity and whether the changed interval had been shorter or longer than the other IOIs.

Results

The average asynchrony, computed across the three pre-P positions, was −45 ms, and individual participant averages ranged from −8 to −79 ms. Relative asynchronies were again computed by subtracting the asynchrony in Position P plus Δt from all following values. These following values, however, were not expressed as relative asynchronies (as in previous studies of phase shifts) but rather as *relative deviations* of the taps from the extrapolated original phase of the sequence (i.e., from integer multiples of 500 ms, as if there had been an EOS instead of a phase shift). This was done to make the PCR in Position P + 1 directly comparable with that in Experiment 5. Subsequent relative deviations were expected to converge upon Δt, the goal of phase correction.[6]

Figure 9 compares the average PCRs in Experiments 5 (EOSs) and 6 (phase shifts). Figure 9a shows that, as predicted, the PCRs to large phase shifts were substantially larger than the PCRs to large EOSs. Whereas the PCRs to EOSs reached an asymptote around ±100 ms, the PCRs to phase shifts continued to increase with perturbation size across the whole range. Figure 9b shows the results for small perturbations in greater detail. Here, it is evident that there was little difference across experiments in the PCRs to small positive perturbations, but the PCRs to small negative phase shifts were clearly larger than those to equally small EOSs. The PCRs to phase shifts were symmetric; the asymmetry observed previously in one experiment with small phase shifts (Repp, 2000, Experiment 5) thus was not replicated.

Repeated measures ANOVAs were conducted on the PCR data of the 6 individuals who participated in both Experiments 5 and 6, separately for large and small perturbations. The variables were experiment (2), direction (2), and magnitude (5), and the sign of the deviations for negative perturbations was reversed. For large perturbations, there was a significant main effect of experiment, $F(1, 5) = 21.0$, $p < .006$, which confirmed that the PCRs were larger for phase shifts than for EOSs. The main effect of magnitude was also significant, $F(4, 20) = 10.0$, $p < .0002$, as was the Experiment × Magnitude interaction, $F(4, 20) = 7.0$, $p < .002$, which reflected the fact that the difference between experiments increased with absolute perturbation magnitude. The ANOVA on the data for small perturbations yielded only a significant main effect of magnitude, $F(4, 20) = 15.1$, $p < .0001$. Surprisingly, there were no significant effects involving experiment. Therefore, another ANOVA was conducted on the PCRs to small perturbations, which included the data of all 8 participants in each experiment, treating them as independent groups. Here, in addition to the significant main effect of magnitude, $F(4, 56) = 27.8$, $p < .0001$, there were significant main effects of experiment, $F(1, 14) = 5.4$, $p < .04$, and of direction, $F(1, 14) = 5.4$, $p < .04$, as well as a Direction × Magnitude interaction, $F(4, 56) = 3.5$, $p < .02$. However, the other interactions fell short of significance, so that the finding of a larger difference between experiments for small negative than for small positive perturbations (Figure 9b) cannot be considered representative of all participants.

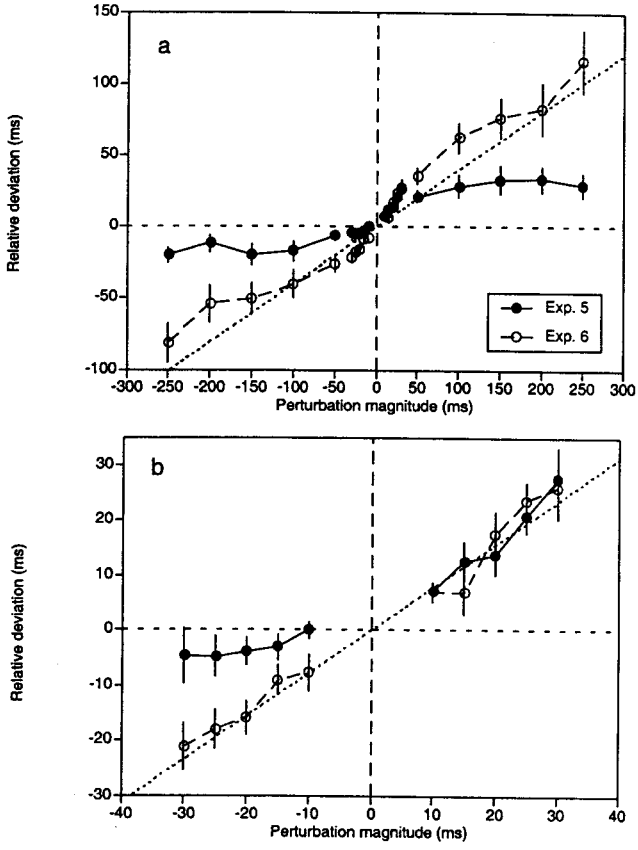

Figure 9. Average phase correction responses (Position P + 1) to event onset shifts (Experiment 5) and phase shifts (Experiment 6), with standard errors (across participants). (a) Whole range. (b) Narrow range only. Exp. = Experiment.

With regard to the validity of the linear phase correction model, it should be noted first that it is supported by the data for small phase shifts (Figure 9b). These data are fit well by a straight line through the origin ($r = .98$), as shown by the dotted line in the figure. The slope of the line is 0.78, which is relatively steep for this sequence tempo. (Error correction parameters of about .5 are more typical; see Pressing, 1998; Repp, 2000, 2001a; Semjen et al., 2000.) The data for the wide range of phase shifts (Figure 9a) are less convincingly linear, but nevertheless can be described

[6] For the largest perturbations, divergent compensatory strategies were sometimes observed, such as skipping or adding a tap (cf. Semjen et al., 1998). These trials, which were small in number, were excluded from the average asynchronies. For one participant, no representative average PCR could be determined for phase shifts of +250 ms; a reasonable estimate was substituted in the statistical analyses.

reasonably well by a straight line (r = .95). However, the slope of that line is only 0.40, about half that of the regression line for small phase shifts. Thus, the relative PCRs were definitely smaller for large than for small phase shifts. In fact, if the data points for the largest changes (±250 ms) are discounted, the PCR function has a distinct sigmoid shape, which seems more consistent with the functions assumed by dynamic systems approaches than with the linear phase correction model. However, an explanation for the relatively more effective phase correction for the largest shifts (±250 ms) would have to be found. Individual slopes of regression lines ranged from 0.19 to 0.78 for all phase shifts combined, and from 0.22 to 1.18 for small changes only. Thus, there were large individual differences in the PCR function. Some individuals were able to compensate immediately for small phase shifts (slope = 1), but none was able to do so for large phase shifts.

Regression lines were also fit to the relative deviations in Positions P + 2 to P + 5 (not shown in Figure 9), first for all phase shift magnitudes combined and then for small changes only. This was done for each participant individually. Figure 10 shows the average slopes of these regression lines as a function of position, with standard errors. Because relative deviations from the original phase rather than relative asynchronies were analyzed, the slopes were expected to converge on 1, indicating that the relative deviations approached Δt. The results in Figure 10 show not only that the initial PCR was larger for small than for large phase shifts, but also that the subsequent phase correction was more rapid: On the average, the process was complete in two versus five taps, respectively. The standard errors are rather large for the responses to small changes, due to one participant who yielded anomalous data, suggesting a phase shift rather than phase correction following small phase shifts. Several other participants showed overcorrection of phase (slopes greater than 1) following small phase shifts, especially in later positions. Repp (2001a) has suggested that a period correction process may be engaged in such cases, in addition to phase correction. No such overcorrection was observed for large phase shifts. Despite the one deviant participant, the differences shown in Figure 10 were significant in a repeated measures ANOVA with the variables of range (all changes vs. small changes) and position (5): for the main effect of range, $F(1, 7) = 6.5$, $p < .04$; for the main effect of position, $F(4, 28) = 26.4$, $p < .0001$; and for the interaction, $F(4, 28) = 5.8$, $p < .002$.

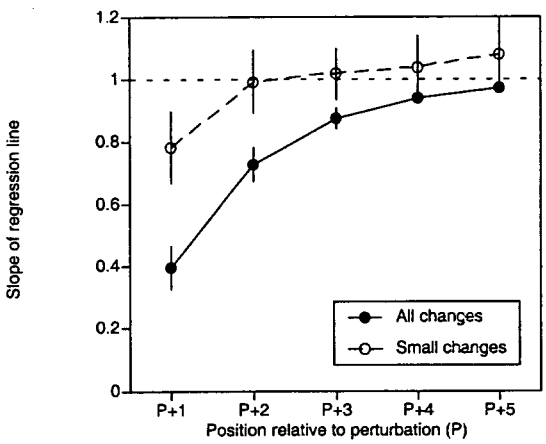

Figure 10. Average slopes of regression lines describing the relative asynchrony as a function of event onset shift magnitude in Experiment 6, with standard errors (between-participants variability). Results are shown for the whole range (*all changes*) and for the narrow range only (*small changes*).

For the sake of completeness, the detection responses are shown in Figure 11. As in the analogous figure for EOSs (Figure 7), the upper panel shows the complete data, whereas the lower panel zooms in on the small changes. The data were quite similar to those of Experiment 5, which suggests that phase shifts and EOSs do not differ much in detectability (see also Friberg & Sundberg, 1995; Schulze, 1978). Although the average detection thresholds (50% crossover points of the correct positive response functions) were similar for negative and positive phase shifts (near ±18 ms), there was again a response asymmetry: The correct response function was steeper for positive than for negative perturbations, and negative phase shifts were more frequently misidentified in the range from ±20 to ±150 ms. An analysis of the asynchronies contingent on detection responses was not deemed necessary, because it is clear from earlier such analyses (Repp, 2000) and from the data in Figure 9b that phase correction in response to phase shifts is independent of awareness of a perturbation.

Discussion

The results of Experiment 6 confirm the interpretation given to the results of Experiment 5, namely that participants were able to voluntarily reduce their PCRs by intending not to react to EOSs. This was mainly true for large EOSs (beyond ±50 ms). Some participants seemed to be able to reduce their PCRs to small, even subliminal, negative EOSs. A skeptic might object that it could have been the nature of the perturbations themselves rather than participants' strategic control that led to the reduced PCRs to EOSs. This seems unlikely: If there was an effect of the perturbations as such, it must have been mediated by participants' knowledge and expectations of a particular kind of change, which in turn led to the intention to react appropriately. To prove this point, however, it is necessary to dissociate perturbations and intentions, which has been done in a subsequent study (Repp, in press).

Experiment 6 also examined the nature of the relationship between PCR magnitude and phase shift magnitude. The results suggest that a simple linear model of phase correction is valid only for relatively small perturbations. There was clear evidence of a reduced efficiency of phase correction for larger phase shifts, which is consistent with dynamic systems models that postulate a nonlinear error correction function. However, it is also possible that the change in slope of the PCR function was in part or wholly an artifact of the blocked presentation of small and large phase shifts. Further investigations using a completely randomized design have since been conducted to confirm the nonlinearity (Repp, in press).

Experiment 7

Experiments 1–5 were concerned with automatic phase correction in response to EOSs. Experiment 7 extended the investigation from phase correction to phase resetting.

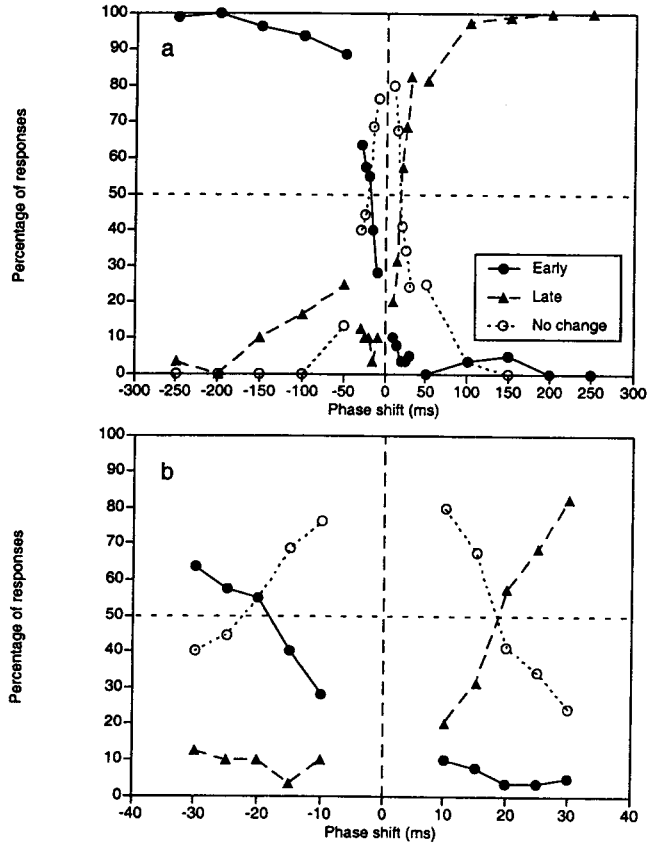

Figure 11. Average percentages of detection responses (*early, late,* and *no change*) as a function of phase shift magnitude in Experiment 6. (a) Whole range. (b) Narrow range only.

Hary and Moore (1985, 1987) have argued that the seemingly continuous phase correction in synchronized tapping results from a random alternation of two discrete phase resetting processes, one occurring with reference to the preceding tap (which means ignoring the sequence, hence zero phase correction) and the other with reference to the preceding sequence event (which means perfect phase correction). Schulze (1992) showed that this model is formally equivalent to the linear phase correction model, with its single parameter being analogous to the proportion of perfect phase resettings in Hary and Moore's model. In an attempt to rationalize the notion of continuous but imperfect phase correction, Repp (2001a) revived the half-forgotten distinction made by Hary and Moore (see also Shaffer, 1982) by proposing that there is a continuous dynamic competition between two opposing forces, which were called *motor persistence* and (stimulus-based) *phase resetting*. Repp showed that perfect phase correction occurs when tapping (re)starts immediately after a small phase shift. When the continuity of the motor activity is disrupted, there is no motor persistence; therefore, perfect phase resetting can occur. Such phase resetting nullifies any immediately preceding phase shift in the tone sequence—a highly desirable outcome when responding to phase shifts.

Experiment 7 extended this new paradigm to EOSs, for which phase resetting is highly undesirable because it creates a large asynchrony. The question was to what extent participants would be able to suppress their *phase resetting response* (PRR) when tapping (re)starts immediately after an EOS. It was expected that, when the EOS is subliminal, the participants' intention not to react to it would have no effect, and complete phase resetting would occur (PRR = 100%). When the EOS is large, partial suppression of the PRR might be possible, but it might be less effective than suppression of a PCR to the same EOS in continuous tapping, because it is not aided by the motor persistence factor that counteracts phase resetting. Suppression of phase resetting would require accurate perceptual extrapolation of the rhythm of the sequence events preceding the EOS while ignoring the shifted tone: The participant must (re)start tapping at a time point corresponding to the original phase of the sequence. However, the perceptual process involved may itself be subject to phase correction following an EOS (Barnes & Jones, 2000; Large & Jones, 1999), and this would lead to inaccurate extrapolation.

There were four conditions in Experiment 7. The first required continuous tapping and was expected to replicate earlier findings of an obligatory PCR to an EOS. In the second condition, following a pitch cue, the tap coinciding with the shifted tone had to be omitted, so that tapping restarted with the tone following the EOS. In the third condition, participants waited for a pitch cue before starting to tap with the tone following the EOS. In both of these conditions, a PRR larger than the PCR in the first condition was expected, because of automatic phase resetting. A difference in results between the second and third conditions would suggest a role of motor persistence from the taps preceding the single omitted tap in the second condition. In the fourth condition, tapping started with the second tone following the EOS. In that case, no effect of the EOS was expected because phase resetting would occur with reference to an unperturbed tone. The first condition, which also included a redundant pitch cue, helped to ascertain any effect that the pitch change itself might have on tap timing. Each condition used both subliminal (±10 ms) and supraliminal (±100 ms) EOSs. (Judging from the results of Experiment 5, ±100 ms seemed a better choice than the ±50 ms used in Experiments 1–4.) In addition, each condition also included isochronous sequences, which served as a baseline to gauge general effects of omitting a tap or starting to tap on cue.

Method

Participants. There were 10 participants in this experiment. Five of them had served in a number of previous experiments; they included myself, the young research assistant, and 3 undergraduates. Five additional participants had no previous tapping experience but were able to tap with low variability right away.[7] Two of them participated later in Experiment 6, and one participated in Experiment 5. (The experiments overlapped chronologically.) They included a research assistant (female, age 31) and a visiting scholar (female, age 26), both with little musical training, as well as a teacher (female, age 37) and 2 graduate students (male, ages 24 and 27), who all had substantial musical training.

Materials. The sequences containing EOSs of ±10 ms and ±100 ms were taken from Experiment 5. In addition, a set of perfectly isochronous

[7] Experiment 7 served as a screening experiment for finding individuals who could tap with low variability. Eight additional participants were tested and rejected. Their data, as far as they were analyzed, were generally consistent with the results reported here.

sequences was included; their length varied likewise from 13 to 17 tones. In each of these sequences, three successive tones were changed to a pitch (E_7: 2638 Hz) that was eight semitones below the pitch of the other sequence tones. The position of these three cuing tones varied, resulting in three stimulus sets. In one set (used in Conditions 1 and 2), the last cuing tone preceded the EOS. In a second set (used in Condition 3), the last cuing tone was the shifted tone. In the third set (used in Condition 4), the second cuing tone was the shifted tone. Each set comprised 25 sequences, five for each of the five perturbation sizes (including zero). Two blocks of 25 sequences each, representing different random orders, were presented in each condition.

Procedure. Participants received printed instructions containing a diagram of an EOS (as in Figure 1c), so they knew that after the EOS the sequences continued in the original phase. The four conditions were presented in fixed order. In Condition 1 (no skip), participants were told to tap regularly and in synchrony with each sequence, starting with the second tone, and not to react to any EOSs or to the lower-pitched tones. In Condition 2 (skip P), 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 in synchrony with the remaining tones. In Conditions 3 (start at P + 1) and 4 (start at P + 2), participants were told not to start tapping until they had heard the three lower-pitched tones. They were asked to get their finger ready on the response key and to start tapping in synchrony with the first high-pitched tone following the cuing tones.

Results

The isochronous sequences served to assess any effects of the pitch change in the sequence and of the various tapping conditions on tap timing. The average raw asynchronies for these sequences are shown in Figure 12, starting with the first low-pitched tone and aligned with respect to that tone. It is clear that the pitch change as such had no influence on the timing of taps in the no skip condition, in which the average asynchrony was rather constant at about −48 ms. Skipping of a single tap resulted in somewhat less negative asynchronies following a skip. (There were considerable individual differences here.) Starting to tap led to substantially less negative asynchronies at the beginning. This tuning in is commonly observed at the beginnings of sequences (Fraisse, 1966; Repp, 2001a; Semjen et al., 1998), but it evidently occurs even when tapping begins in the middle of a sequence. All these results are consistent with those obtained in a previous experiment using similar tapping conditions (Repp, 2001a, Experiment 5).

Because only the no skip condition required a tap in Position P, relative asynchronies in the other conditions could not be computed by subtracting the asynchrony of that tap, as in Experiments 1–6. Instead, relative asynchronies in all conditions were obtained by subtracting the average asynchronies for the isochronous sequences from those for the perturbed sequences. Thus, the tuning-in effects shown in Figure 12 were removed from the relative asynchronies. The results are summarized in Figure 13.

The results for the no skip condition are shown in Figure 13a. They are similar to those obtained in Experiments 1 and 2. A repeated measures ANOVA with the variables of EOS magnitude (2) and direction (2) was conducted on the PCR data; the sign of the relative asynchronies following negative perturbations was reversed.[8] There was only a significant main effect of magnitude, $F(1, 9) = 38.0$, $p < .0003$. That effect was no longer significant when the PCRs were expressed as proportions of perturbation size. The average relative PCRs were 45% for 10-ms shifts and 37% for 100-ms shifts.[9]

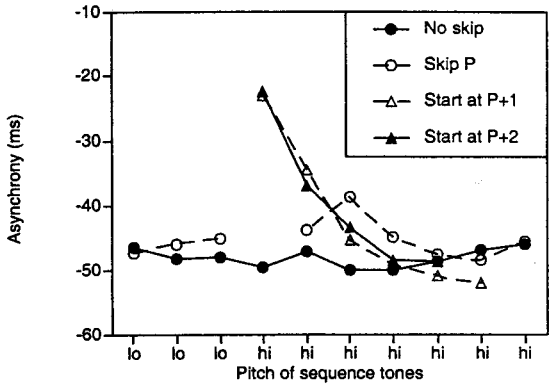

Figure 12. Average asynchronies in four conditions of Experiment 7, aligned with the pitch change from low (lo) to high (hi) tones in the sequence. (No standard errors are shown because they would reflect only large individual differences in the anticipation tendency.)

The skip P and start at P + 1 conditions (Figures 13b and 13c) showed much larger effects of the EOSs on the timing of the following tap, just as predicted. However, there was little difference between the two conditions. Evidently, a single omitted tap was sufficient to cause phase resetting, and the series of regular taps preceding the skip was of little help in reducing the unintended PRR. A repeated measures ANOVA was conducted on the PRR data (Position P + 1) of the two conditions combined, with the variables of condition (2), EOS magnitude (2), and direction (2), with the sign of the relative asynchronies following negative perturbations reversed. In addition to the obviously significant effect of EOS magnitude, there was a marginally significant Magnitude × Direction interaction, $F(1, 9) = 5.6$, $p < .05$, but no significant differences between the two conditions. The interaction was due to a smaller PRR to large negative than to large positive perturbations. However, this interaction did not reach significance when the PRR was expressed as a proportion of perturbation size. In that analysis, only the main effect of magnitude was significant, $F(1, 9) = 9.8$, $p < .02$. On average, the relative PRR to 10-ms EOSs was 99%, which suggests complete phase resetting, just as predicted (individual averages ranged from 62% to 138%), whereas the relative PRR to 100-ms shifts was only 77% (ranging from 47% to 101%). This difference suggests that participants were able to voluntarily reduce their PRR to large perturbations. However, it is also possible that phase resetting is generally incomplete following large perturbations. An experiment analogous to Experiment 6 that investigates intentional phase resetting over a wide range of phase shift sizes remains to be conducted.

Phase resetting to the preceding tone was virtually perfect in the start at P + 2 condition (Figure 13d). Even large perturbations in

[8] To reduce variability, the relative asynchronies in this analysis were further relativized by subtracting the asynchrony in Position P from the subsequent asynchronies.

[9] Figure 13a suggests that small negative EOSs caused a larger PCR than small positive EOSs, contrary to previous results, especially in Experiment 5. However, this asymmetry was reduced and nonsignificant when the asynchronies were recalculated relative to Position P, as was done in the statistical analysis. Still, it raises questions about the reliability of the large asymmetry observed in Experiment 5.

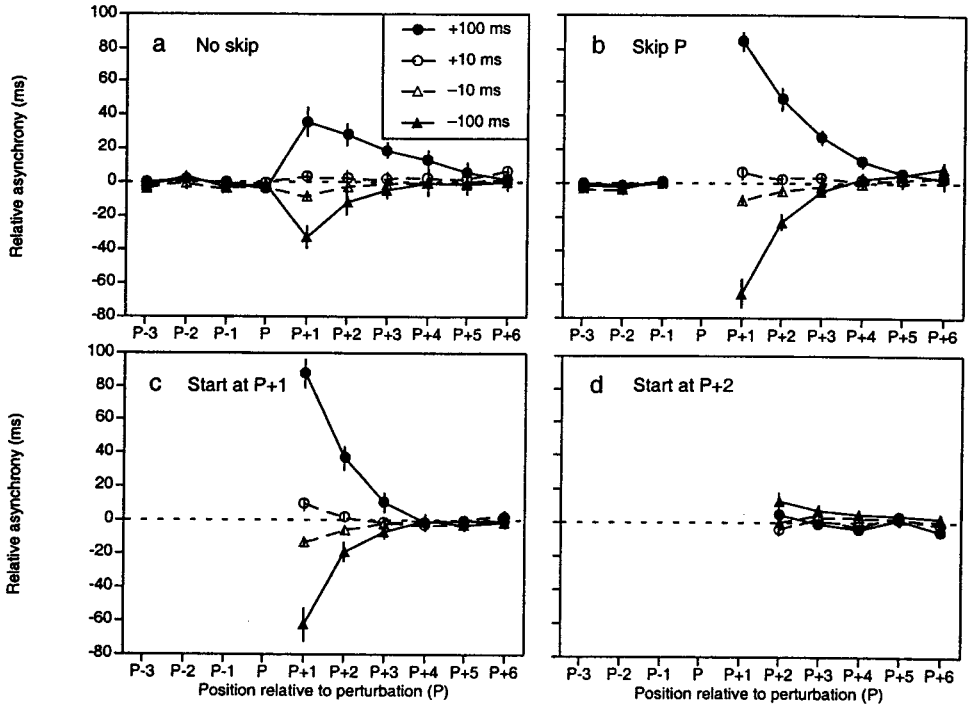

Figure 13. Average relative asynchronies as a function of event onset shift magnitude and sequence position in four conditions of Experiment 7. (a) No skip. Data points are shown in Position P here to distinguish this condition visually from the skip P condition. However, contrary to the *y*-axis label, the data in Position P are not relative asynchronies (expected value = $-\Delta t$), but relative deviations from regularity (expected value = 0). (b) Skip P. (c) Start at P + 1. (d) Start at P + 2. The standard error bars represent between-participants variability.

Position P had no obvious influence on the timing of the first tap. An ANOVA on these PRR data, which was conducted without reversing the sign of the asynchronies following negative EOSs, surprisingly yielded a main effect of direction, $F(1, 9) = 5.9, p < .04$, indicating that asynchronies were more positive (less negative) following negative EOSs than following positive EOSs (contrary to what was observed in the other conditions). This effect, which was small in magnitude but consistent across participants, is difficult to interpret.

Discussion

This experiment confirmed the prediction that omission of the tap coinciding with an EOS or starting to tap immediately after an EOS would result in a larger unintended effect on tap timing than when tapping is uninterrupted. Indeed, when the EOS was subliminal, there was complete phase resetting (on the average) after an interruption of tapping. Following supraliminal EOSs, phase resetting was not complete, but it is not yet clear whether that represented successful voluntary reduction of the PRR or simply weaker phase resetting after large EOSs. The results are consistent with the hypothesis that phase resetting is inhibited by a resistance of the cyclic motor activity to perturbation. When that inhibition is removed by disrupting the motor activity, complete phase resetting becomes possible and indeed obligatory.

The results are also interesting from a perceptual perspective. Apparently, participants (without exception) were unable to predict accurately when the tone following an EOS would occur. In other words, they were unable to extrapolate the original phase of the sequence through the shifted tone. It seems that the shifted tone led to a shifted temporal expectation, equivalent to a phase shift, or indeed phase resetting, of an attentional oscillator (Large & Jones, 1999). That oscillator seems to be closely coupled to the processes that control the timing of the motor activity. The present results are consistent with those of Barnes and Jones (2000), who demonstrated large biases in judgments of interval duration following a single shifted tone.

General Discussion

The Automatic Nature of Phase Correction

The present series of experiments investigated the automaticity of phase correction in sensorimotor synchronization by focusing on a situation in which this useful process is undesirable and unintended. EOSs—in contrast to the ubiquitous self-generated timing variability, which requires phase correction to maintain perceived synchrony, and in contrast to experimenter-introduced phase shifts in a sequence, which require phase correction to reestablish synchrony—do not require any corrective action. The best strategy would be to ignore them and to tap as regularly as possible through the perturbation. This was the participants' intention in the present experiments (except for Experiment 6). However, the results show clearly that phase correction cannot be

avoided. Even the most experienced participants invariably evinced a PCR. Thus, the results suggest that phase correction is at least in part an automatic process that is not under participants' voluntary control.

This conclusion is further supported by evidence that the PCR is independent of the perceptual detection threshold for EOSs. Neither the PCR to EOSs (Experiment 5) nor that to phase shifts (Experiment 6; see also Repp, 2000) showed any tendency to abate below the detection threshold, which was near ±20 ms (4% of the baseline IOI) in both experiments. Although the threshold could be defined differently or be assessed with different methods, the values obtained here are generally consistent with the literature. Therefore, it may be concluded that phase correction does not require awareness of temporal change.

The present experiments provide evidence, however, that the intention not to engage in phase correction can reduce the PCR to large perturbations. This result emerged most clearly from Experiment 5, in which the average PCR to large EOSs (±100 ms or larger) was shown to reach an asymptote. It was hypothesized here that the asymptotic PCR may be related to the detection threshold for irregularities in one's own tapping. It seems that participants were generally successful in preventing themselves from becoming aware of their own PCRs, although this claim is in need of stronger support. The intention to tap as regularly as possible may involve an increased attentional focus on the motor persistence factor that inhibits phase correction during continuous tapping, as hypothesized by Repp (2001a). However, a mere change of the relative weights of two competing tendencies (motor persistence and phase resetting) would result in a proportional reduction of the PCR across the whole range, which is not what was observed. The control strategy somehow set an upper limit to the PCR, and this indicates a nonlinear process whose nature needs to be clarified in further research.

Although phase correction takes place without awareness, it is possible that awareness of an EOS is required to keep the PCR within bounds. The positive and negative EOS magnitudes at which the PCRs reached their asymptotes coincided approximately with the points at which correct detection responses approached 100%. However, this does not prove a causal relationship, and an analysis of PCRs contingent on detection responses proved inconclusive. Awareness of an EOS may be necessary but not sufficient for PCR suppression.

In Experiment 5, the PCRs to small (often undetected) negative EOSs were substantially smaller than those to equally small phase shifts or to positive EOSs, which suggests suppression without awareness, but there were large individual differences in that regard. Also, the asymmetry in PCRs to small positive and negative EOSs was less pronounced or absent in other experiments in this study. A recent experiment (Repp & Penel, in press), which varied EOS magnitude from −80 ms to +80 ms in 10-ms steps, found that average PCRs increased linearly with both negative and positive EOS magnitudes up to at least ±60 ms, but with a shallower slope on the negative side. Thus, the asymmetry seems to be real, but it is not usually as pronounced as it was in Experiment 5. To rule out any artifacts of the blocked design used in Experiments 5 and 6, replications with complete randomization of all EOS magnitudes have also been conducted and will be reported in a forthcoming article (Repp, in press).

Experiment 7 examined the automaticity of phase resetting. Phase resetting occurs when the phase correction process is released from the inhibition that motor persistence exerts on it (Repp, 2001a). Phase resetting proved to be difficult to prevent or reduce. This is consistent with the general idea that PCR suppression involves an attentional focus on the motor activity. When the motor activity is disrupted, such a focus is not possible. Moreover, neither the continuous activity preceding a single skipped tap nor the perceptual tracking of the isochronous sequence preceding an EOS were of much help in reducing phase resetting. Although some reduction was evident for large EOSs (±100 ms), it could be that phase resetting is generally less complete following large phase perturbations; this remains to be investigated. What is clear from the results of Experiment 7 is that the PRR cannot be held within the same narrow limits as the PCR in continuous tapping.

It is believed that participants were generally not aware of the extent of their phase resetting, despite the large asynchronies that it generated. The perceptual threshold for an irregularity in one's own tapping is likely to be elevated following a short or long interruption in the motor activity, because interval discrimination is affected by the duration of adjacent intervals (see, e.g., Hirsh et al., 1990). Also, the perceptual process that is engaged in following and predicting the sequence events may itself be subject to phase correction and therefore may generate misleading expectations about the event following an EOS (Barnes & Jones, 2000; Large & Jones, 1999). Therefore, it is conceivable that the large phase resetting response falls within the same perceptual constraints that govern the smaller PCRs to EOSs in continuous tapping, namely participants' perception of the regularity of their own tapping.

Inphase Versus Antiphase Tapping

Experiment 2 demonstrated that the average PCR to EOSs is equally large in inphase and in antiphase tapping. Analogous results have been obtained by Repp (2001a) for phase shifts, in which the PCR was intended. These results do not support the hypothesis that sensorimotor coupling is less strong in antiphase than in inphase relationships (Kelso et al., 1990; Kelso & Kay, 1987; Wimmers, Beek, & Wieringen, 1992). This hypothesis was based on dynamic systems theory postulating coupled nonlinear oscillators. If oscillator coupling is necessarily weaker in antiphase than in inphase, then perhaps this model is not the best metaphor for what happens in sensorimotor synchronization.

Semjen and Ivry (2001) have questioned the coupled-oscillators model in the case of bimanual coordination and have proposed instead that coordination results from the control of specific time intervals (i.e., rhythms), especially when the action produces auditory feedback and thus participates in generating a rhythm. Antiphase tapping with auditory feedback generates an isochronous rhythm with an IOI half that of the sequence, and participants presumably maintain this isochrony by making the intervals preceding and following a tap perceptually equal. Although antiphase tapping is not as easy and natural as inphase tapping, it is aided by the subdivision of sequence IOIs, which leads to a reduction in perceptual and motor variability (unless the tempo is rather fast), making antiphase tapping as accurate as (or even more accurate than) inphase tapping and hence equally responsive to timing perturbations (Semjen, Schulze, & Vorberg, 1992; Vos & Helsper,

1992). By contrast, tasks in which antiphase coordination has been observed to be less stable than inphase coordination generally have not involved auditory rhythms but visual signals and/or silent limb movements, as well as systematic accelerations of tempo (Kelso et al., 1990; Wimmers et al., 1992). The privileged connection of auditory rhythms to movement was pointed out long ago by Fraisse (1948). Also relevant is the recent argument of Robertson et al. (1999) and Zelaznik, Spencer, and Doffin (2000) that finger tapping is more of a discrete interval production task than a continuous oscillatory movement.

A difference between inphase and antiphase conditions also failed to emerge in Experiments 3 and 4, in which the terms refer to the location of EOSs relative to the target sequence in two alternating sequences of the same tempo. Perturbations located in the target (inphase) sequence elicited the same average PCR as perturbations located in the distractor (antiphase) sequence. However, these PCRs were smaller than those observed in the single-sequence inphase and antiphase tapping conditions of Experiments 1 and 2. Thus, the PCR to a perturbed target tone was diminished when an unperturbed distractor tone occurred 250 ms before the next tap, and the response to a perturbed distractor tone was reduced when the preceding tap had coincided with an unperturbed target tone. One way of conceptualizing these situations is that participants treated the interleaved sequences as a rhythm with a two-level metrical structure (IOIs = 250 and 500 ms) and gave equal weight to perturbations occurring within the interval corresponding to the higher level of the meter (IOI = 500 ms). Error correction in the context of complex rhythmic and metrical structures is an interesting topic that I am currently pursuing. The method of probing participants' mental representations of rhythms with EOSs holds some promise, though it may turn out that phase correction is too elementary a process to be affected by metrical hierarchies.

Phase Correction and Stream Segregation

Experiments 1, 3, and 4 constitute a preliminary exploration of the relationship between error correction in synchronization and auditory scene analysis (Bregman, 1990). The consequences of auditory scene analysis are usually observed in perceptual judgments of various kinds. Phase correction, however, is an automatic, subconscious process that may well precede, or be functionally independent of, such judgments and of the processes underlying them. In other words, PCRs may be based solely on the temporal onsets of events, without regard to their pitch, timbre, or loudness. If so, this may be considered a form of "direct parameter specification" (Neumann, 1990) in which the only parameter is time. Näätänen and Winkler (1999) have recently summarized the considerable physiological evidence that exists for preperceptual representations of auditory stimuli in the brain. The earliest of these representations seems to be used for transient (i.e., onset) detection, which is all that may be required for phase correction in synchronization.

Repp (2000, Experiments 3–5) has demonstrated that at least three factors that affect the interval discrimination threshold or exert a bias on judged interval duration do not affect phase correction following subliminal phase shifts. One of these factors was a moderate pitch change in the sequence at the point of the perturbation. The present Experiment 1 introduced a much larger pitch difference, albeit only in a single tone, which likewise did not affect phase correction significantly. Although it was not shown directly in Experiment 1 that the pitch manipulation affected explicit timing judgments, various results in the literature suggest that such a large pitch difference would increase the interval discrimination threshold and lengthen the subjective duration of at least one of the adjacent intervals (e.g., Crowder & Neath, 1994; Divenyi & Sachs, 1978; Hirsh et al., 1990; Perrott & Williams, 1971; Shigeno, 1986). The negative finding of Experiment 1 suggests that the interval discrimination threshold is irrelevant to phase error correction and that the temporal position of the low tone was registered accurately by the phase correction process.

Experiment 4 further probed the connection between stream segregation and phase correction by greatly increasing the pitch separation of the two interleaved sequences used in Experiment 3. Remarkably, this manipulation had no effect: Inphase and antiphase perturbations still elicited equal average PCRs, suggesting that the two sequences were still treated as an integrated rhythm. Although perceptual segregation was not assessed directly in Experiment 4, data in the literature (e.g., Brochard et al., 1999) suggest that a 20-semitone pitch separation increases the perceptual segregation of two sequences relative to a 3-semitone separation. Thus, it is possible that phase correction operates on temporal information derived from a processing stage that precedes or runs in parallel with auditory scene analysis. At least this seems to be the case in the large parameter space in which integration and segregation are subject to voluntary control. Whether it also holds in the case of obligatory integration or segregation effects that have been attributed to processes in the auditory periphery (Beauvois & Meddis, 1996; Rose & Moore, 2000; but see also Carlyon, Cusack, Foxton, & Robertson, 2001) remains to be investigated.

The Linear Phase Correction Model

A linear phase correction model with a single parameter (Mates, 1994a, 1994b; Pressing, 1999; Semjen et al., 2000; Vorberg & Wing, 1996) accounts well for phase correction in synchronization with isochronous sequences (Pressing, 1998; Semjen et al., 2000) or with randomly or systematically perturbed sequences (Pressing, 1998; Repp, 2000; Schulze, 1992; Semjen et al., 1998). Nevertheless, some limitations of this simple model are evident. Pressing (1998) and Semjen et al. (1998) noted that, at fast tempi and/or with expert tappers, a second parameter referring back to the penultimate asynchrony may be needed. Repp (2000, 2001a) noted some deviations from the predictions of the model that may be due to simultaneous engagement of a period correction process. Experiment 6 investigated phase correction over a wide range of phase shift magnitudes and demonstrated that the PCR is not linearly related to perturbation magnitude over the whole range. Rather, different relationships seem to hold for small and for large perturbations, with phase correction being more effective (judging from the immediate PCR) for the former than for the latter. This was not due to the blocked presentation of two different ranges of phase shift magnitudes (Repp, in press). The present data suggest that the simple linear phase correction model may be valid only within the narrow range of asynchronies that are representative of those encountered in synchronizing with isochronous sequences. To explain phase correction in response to large perturbations, a nonlinear error correction function may have to be assumed (En-

gbert et al., 1997; Large & Jones, 1999; Pressing, 1999; but see also Semjen et al., 1998). Obviously, if the model were to account for the response to EOSs, it would have to include an additional nonlinear control function that represents participants' intention not to react to the perturbations.

The observed nonlinearities pertain primarily to the initial PCR. In the present study, little attention was paid to the subsequent correction of the asynchrony caused by the PCR. This subsequent correction was not expected to be affected by participants' intention not to react to EOSs; on the contrary, it was congruent with their intention to stay in synchrony with the sequence. In general, this subsequent phase correction seemed to follow the curvilinear (exponential) function that is predicted by the linear error correction model. A precise quantitative account of the data, which was not attempted here, naturally would have to consider the complete time course of phase correction.

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