Phase Correction, Phase Resetting, and Phase Shifts After Subliminal Timing Perturbations in Sensorimotor Synchronization

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Recent studies of synchronized finger tapping have shown that perceptually subliminal phase shifts in an auditory sequence are rapidly compensated for in the motor activity (B. H. Repp, 2000a). Experiment 1 used a continuation-tapping task to confirm that this compensation is indeed a phase correction, not an adjustment of the central timekeeper period. Experiments 2–5 revealed that this phase correction occurs even when there is no ordinary sensorimotor asynchrony—when the finger taps are in antiphase or arbitrary phase relative to the auditory sequence (Experiments 2 and 3) or when the tap coinciding with the sequence phase shift is withheld (Experiments 4 and 5). The phase correction observed in the latter conditions was instantaneous, which suggests that phase resetting occurs when the motor activity is discontinuous. A prolonged phase shift suggestive of overcompensation was observed in some conditions, which poses a challenge to pure phase correction models.

There is mounting evidence that sensory information can guide action without (or before) being consciously perceived. Neumann (1990a), in a key article, called such guidance *direct parameter specification*. Most of the evidence comes from vision research. For example, masked visual stimuli that are not consciously perceived can nevertheless cue manual responses (Fehrer & Raab, 1962; Klotz & Neumann, 1999; Klotz & Wolff, 1995; Neumann & Klotz, 1994; Taylor & McCloskey, 1990) and activate corresponding motor areas in the brain (Eimer & Schlaghecken, 1998; Leuthold & Kopp, 1998). Manual actions such as pointing, grasping, and gesturing seem to be controlled directly by visual information and thus are immune to illusions that distort conscious perception (Adam et al., 1996; Agliotti, DeSouza, & Goodale, 1995; Bridgeman, Kirch, & Sperling, 1981; Creem & Proffitt, 1998; Gentilucci, Chieffi, Daprati, Saetti, & Toni, 1996; Haffenden & Goodale, 1998; Rumiati & Humphreys, 1998; but see Franz, Gegenfurtner, Bülthoff, & Fahle, 2000, for a recent critique). Following the seminal work of Ungerleider and Mishkin (1982), Goodale and coworkers have accumulated evidence for anatomically and functionally separate visual pathways subserving object perception and the control of action (see, e.g., Goodale & Humphrey, 1998; Goodale & Milner, 1992). Striking cases of functional dissociation of these pathways have been observed in neurological patients in the form of blindsight and visual form agnosia on one hand, and optic ataxia on the other (Goodale & Humphrey, 1998; Köhler & Moscovitch, 1997).

There are fewer known instances of similarly direct parameter specification in the auditory modality, and there also seems to be no evidence (as yet) of separate auditory pathways subserving perception and action. Alvin Liberman and his colleagues, however, have long argued that speech perception is not mediated by general processes of auditory perception; in their view, acoustic phonetic information directly specifies the articulatory gestures involved in speech production (see, e.g., Liberman & Mattingly, 1985). These authors have drawn a parallel with auditory localization, a specialized perceptual system that relies on sensory information (interaural differences in time, intensity, and spectrum) so subtle as to be totally inaccessible to conscious perception; what is perceived is the location of the sound source, not the sensory information specifying it. Auditory localization, of course, directly subserves action, as it involves orienting toward or away from a sound source. Therefore, it may be considered a form of direct parameter specification. Phonetic information, too, may directly specify parameters for articulation, as evidenced in close shadowing tasks in which one speaker echoes another's words at a time lag too short to permit full perceptual processing (Chistovich, Aliakrinskii, & Abulian, 1960; Marslen-Wilson, 1985; Porter & Castellanos, 1980; Porter & Lubker, 1980). In commenting on these findings, Fowler (1986) argued that the primary function of (direct) perception is to guide action, a view shared by ecological psychologists and dynamic systems theorists. These considerations provide a broad theoretical context for the present research.

A simple paradigm for investigating auditorily guided action is sensorimotor synchronization, which is an instance of a referential or feedback-controlled activity (Pressing, 1999). The task typically requires finger tapping in synchrony with a sequence of sounds. The synchronization error or phase error—the asynchrony between the time of a tap and the onset of a sound, as registered by the perceptual-motor system—provides information that influences the timing of the next tap. This compensatory process is known as phase (error) correction. A model in which the asynchrony at time t is a linear function of the asynchrony at time $t - 1$ provides a good account of synchronization with isochronous sequences at slow to moderate rates (Mates, 1994a, 1994b; Pressing, 1998, 1999; Semjen, Schulze, & Vorberg, 2000; Semjen, Vorberg, &

Schulze, 1998; Vorberg & Wing, 1996). The slope of the function is a measure of the efficiency of phase correction, with 0.5 being a typical value for moderate tapping rates such as 2 taps/s (Repp, 2000a; Semjen et al., 2000).

Researchers in this area have often hypothesized that phase error correction is limited by the perceptual threshold for the temporal order of the two relevant events, such as a tone and a tap (e.g., Mates, 1994b; Michon, 1967; Pressing & Jolley-Rogers, 1997; Voillaume, 1971; Vorberg & Wing, 1996). This *threshold hypothesis* illustrates a widespread, often tacit assumption that conscious perception mediates between sensory information and action, an assumption that has been questioned by Neumann (1990a), among others. The results of recent experiments (Repp, 2000a) argue strongly against the threshold hypothesis. Phase error correction in sensorimotor synchronization seems to be an automatic, subconscious process that is sensitive to temporal order information well below the perceptual threshold. (Findings consistent with that conclusion have also been reported by Hary & Moore, 1985, 1987; Thaut, Miller, & Schauer, 1998; Thaut, Tian, & Azimi-Sadjadi, 1998.) It is worth noting in this connection that unlike discrimination along some other psychophysical dimensions (e.g., pitch or brightness), the discrimination of temporal intervals and relationships is not limited by the resolving power of a specific sensory organ. It is quite plausible that small timing differences are registered in the brain for purposes other than conscious perception. An obvious case in point is auditory localization. Temporal discrimination thresholds seem to arise at a central processing level at which conscious decisions are made, not at a peripheral filter.

When the auditory stimulus sequence in a synchronization task is perfectly isochronous, the tap–tone asynchronies caused by uncontrollable variability in tap timing constitute the only source of information on which error correction can be based.[1] Because the sequence period is constant, it does not provide any information except at the very beginning, when the participant needs to establish the appropriate tempo for the finger taps, which is usually achieved after about 3 taps (Fraisse, 1966; Semjen, Vorberg, & Schulze, 1998). However, when a timing perturbation is introduced in the stimulus sequence, this necessarily affects both the sequence period and the tone–tap asynchrony, at least momentarily. Therefore, there are now two potential sources of sensory information that may cause the motor activity to adapt to the change in the sequence: The change in asynchrony may lead to an adjustment of the relative phase of the tapping without changing the period of the underlying timekeeper (i.e., a phase correction) and/or the change in stimulus period may lead to an adjustment of the timekeeper period (a period correction). The idea that phase correction can be performed independently of period correction has been promoted by Mates (1994a, 1994b), Vorberg and Wing (1996), Semjen et al. (1998), and Large and Jones (1999), among others. It should be noted that the timekeeper period is not directly observable. What is observable is the period of the motor activity (the intertap interval), which is influenced by both phase correction and period correction. Similarly, the observable relative phase between taps and tones (the asynchrony) is affected by both correction processes.

Because phase correction and period correction have the same behavioral manifestations during synchronization, there is a fundamental ambiguity in this two-tiered model of error correction (Mates, 1994a): Any observed compensation for a timing perturbation in the sequence could be due to either process or to both working in concert. (See Appendix A for a formal derivation of this fact.) To be sure, which of the two error-correction processes is used or which of them predominates if they are employed simultaneously is likely to depend on the nature of the timing perturbation. Consider the two simple kinds of perturbation illustrated in Figure 1: A pulse change (Michon, 1967) or phase shift (Figure 1a) is a local change in the sequence period (the tone interonset interval or IOI) that shifts the relative phase of the isochronous sequence from that point on; a step change or tempo change (Figure 1b) is a persistent change in sequence period that also shifts the relative phase progressively from that point on. It seems plausible that pulse changes will primarily elicit phase correction, whereas step changes will primarily elicit period correction in synchronized tapping. There is no need to change the timekeeper period in response to a pulse change because a phase adjustment is sufficient. It would seem inefficient to adjust to a phase shift by briefly changing the timekeeper period and then changing it back to the original period; yet this is a theoretical possibility that cannot be ruled out immediately. A step change does require a phase correction in addition to a period correction in tapping, but the period correction seems primary: It would seem awkward to keep up with a new sequence tempo by adjusting the phase of each tap without ever changing the timekeeper period. Yet this, too, is theoretically possible. Clearly, plausibility arguments alone cannot reveal what mixture of processes is at work because the two underlying correction processes have exactly the same behavioral manifestations.

Note that at the time of a perturbed event (i.e., at 2,100 ms in Figure 1), a tapping person's perceptual-motor system does not "know" whether the perturbation is a pulse change or an incipient step change. If the next sequence IOI has the same duration as the preceding one, a step change seems more likely, but it could also be a "long pulse," that is, a change in only two successive IOIs. If there are three successive IOIs of the same duration, a step change seems even more likely, and so on. Thus, it seems likely that the error correction process evolves dynamically in concert with the temporal structure of the stimulus sequence, with initial phase correction gradually being replaced by period correction as the evidence for a step change accumulates.

When timing perturbations are readily noticeable, conscious strategies and expectations may come into play that change the deployment and relative efficiency of the two error-correction processes. Although these strategies are of interest in their own right, the present study is specifically concerned with automatic processes of error correction that take place without awareness. (See Wing, 1977b, for arguments in favor of this approach.) This

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[1] The asynchronies between taps and tones typically vary around a negative mean value (i.e., taps precede tones), which presumably corresponds to a registered zero phase error. Many explanations have been proposed for this anticipation tendency (see, e.g., Aschersleben & Prinz, 1997; Vaughan, Mattson, & Rosenbaum, 1998; Wohlschläger & Koch, 2000), but the present study is concerned mainly with error correction, not with explaining the anticipation tendency.
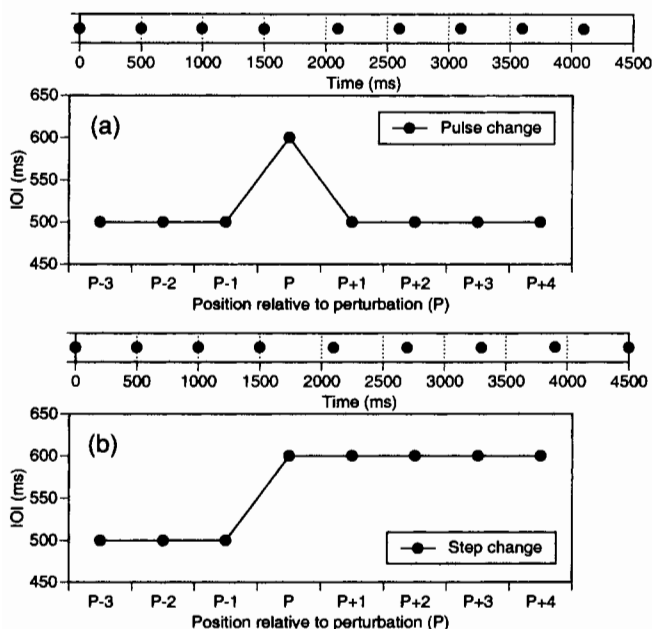
Figure 1. Two kinds of simple timing perturbation in isochronous sequences: (a) pulse (phase) change, (b) step (tempo) change. In each case, the initial period is 500 ms and $\Delta t = 100$ ms. The display above each panel shows tone onsets as a function of time, whereas the panels themselves show interonset interval (IOI) duration as a function of position in the sequence. Note that, for better visibility, Δt in this figure is an order of magnitude larger than Δt values in the experiments.

concern required the use of subliminal timing perturbations.[2] A recent series of experiments (Repp, 2000a) has demonstrated that perceptually subliminal pulse changes in a tone sequence are compensated for rapidly (within 1–3 taps) in synchronized tapping. The pulse changes were between 0.8% and 2% of the sequence IOI duration (500 ms), whereas changes of 4–5% were required for 50% correct detection in a yes–no paradigm (Repp, 2000a, Experiment 5). Consequently, the adjustments in motor control occurred without participants' awareness. Contingency analyses of the data suggested that the average results were not due to intermittent compensation for those asynchronies that, because of motor variability, happened to exceed the perceptual threshold for temporal order. In fact, such asynchronies were rare because participants were very poor at judging the temporal order of taps and tones (Repp, 2000a, Experiment 2). The average results were consistent with models that assume linear phase correction without any perceptual threshold intervening and without any additional period correction (Pressing, 1998; Vorberg & Wing, 1996). However, the theoretical possibility remained that period correction was involved. Repp (2000b) performed a second contingency analysis of his earlier data to address this issue, but the results were not conclusive. A need for further examination of this issue remained.

Experiment 1 therefore investigated the relative roles of phase and period correction in response to subliminal pulse and (incipient) step changes. The hypothesis was that the timekeeper period adapts only gradually to a new sequence tempo and that, therefore, period correction plays only a minimal role in compensating for pulse changes. A synchronization-continuation tapping paradigm

(Stevens, 1886; Wing & Kristofferson, 1973) was used for that purpose, as described in more detail below. By establishing more clearly that subliminal pulse changes only elicit phase correction, the results of Experiment 1 set the stage for the subsequent Experiments 2–5, which concerned the informational role of the sensorimotor asynchrony in phase correction. In particular, these experiments addressed the question of whether phase correction in response to pulse changes requires the registration of a deviation from subjective synchrony (zero phase error). To that end, the experiments used tapping regimes that prevented taps from falling in the vicinity of the perturbed tone, such as tapping in antiphase (Experiment 2) or arbitrary phase (Experiment 3) relative to the sequence tones, withholding the tap coinciding with a perturbation (Experiment 4), and starting to tap only after a perturbation had occurred (Experiment 5). If rapid phase correction occurred under these conditions, it would suggest that subliminal pulse changes can be registered in ways other than deviations from subjective synchrony. One such alternative might be to compare a cognitive temporal prediction or expectancy with the perturbed tone onset. Cognitive predictions could be generated by an attentional oscillator (Large & Jones, 1999; see also Jones, 1976; Jones & Boltz, 1989; Jones & Yee, 1997; Klein & Jones, 1996; McAuley & Kidd, 1998) that is coupled to, or even identical with, the timekeeper or oscillator that controls the tapping period.[3] Results suggesting a role of such a process in motor compensation for subliminal timing perturbations would increase its explanatory value because it has so far only been adduced to account for explicit perceptual judgments. As will be seen, however, alternative interpretations were also considered and ultimately preferred.

Experiment 1

The task in this experiment was synchronized tapping followed by free tapping at the same rate. However, the task differed from the standard synchronization-continuation paradigm (Stevens, 1886; Wing & Kristofferson, 1973) in that a small timing perturbation (a pulse change or incipient step change) occurred at the end of the tone sequence. A crucial assumption underlying this approach was that the rate of continuation tapping would reflect the state of the timekeeper period at the end of the sequence. Because continuation tapping lacks a concurrent external reference, I assumed that no further period or phase correction would occur during the continuation period. Thus, continuation tapping was used as a probe into the state of the timekeeper at the offset of the sequence. The effect on continuation tapping of a single changed IOI at the end of the sequence (a pulse change) was compared with that of three or five changed IOIs (incipient step changes). It was expected that period correction would increase with the number of

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[2] It is not claimed here that these timing perturbations never reached the participants' awareness. The term *subliminal* only implies that the perturbations were generally well below the detection threshold (50% correct in a yes–no paradigm, or 75% correct in a forced-choice paradigm), as inferred from earlier psychophysical studies. Note that if error correction depended on conscious detection of discrepancies, then correction should be imperfect as long as detection is imperfect.

[3] For a discussion of the differences between timekeepers and oscillators, see Beek, Peper, and Daffertshofer (2000). These differences will not be emphasized here and the terms will be used interchangeably.

changed IOIs and that this would be reflected in the tempo of the continuation tapping. The main purpose of the experiment, however, was not to map out the time course of period correction (for that, see Repp, in press) but rather to establish that a pulse change elicits very little period correction.

Method

Participants. The 8 participants had served in earlier finger-tapping experiments and had been selected for their ability to tap with fairly low variability. They included 4 men (29–54 years old) and 4 women (about 19 years old). Three of the men had advanced musical skills; they included 2 graduate students of music theory who played guitar and cello, respectively, and myself, an amateur pianist. The other 5 participants had some musical training but did not play instruments at advanced levels. The differences in age and musical experience between the men and the women (Yale undergraduates) were accidental and, like the sex difference itself, largely irrelevant to the study.

Stimuli. The auditory sequences were produced on a Roland RD-250s digital piano via a musical instrument digital interface (MIDI) under control of a MAX patch (Version 3.0; Zicarelli & Puckette, 1995) running on a Macintosh Quadra 660AV computer.[4] Each stimulus sequence consisted of 11 high-pitched digital piano tones of constant frequency (C_8, MIDI pitch 108, fundamental frequency 4168 Hz), followed, after an interval of 5–6 s of silence, by a single tone of lower pitch (E_7, MIDI pitch 100, fundamental frequency 2638 Hz), which served as a signal to stop tapping. The tones had sharp onsets and decayed over time, first rapidly and then more slowly (simulating undamped piano strings). There were three baseline IOI durations: 500, 550, and 600 ms. The duration of the continuation-tapping interval following each sequence was 10 times the baseline IOI. Sequences were either completely isochronous or contained changes of +10 or −10 ms (Δt) applied to the final IOI, the final three IOIs, or the final five IOIs. Thus, there were three baseline tempi and seven sequence types, totaling 21 different sequences altogether, which were arranged into five different random orders (blocks of trials).

Procedure. Participants sat in front of a computer monitor that 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 right index finger in synchrony with the sequence tones. Participants held the controller on their laps, and they were told that they should move their tapping arm from mainly the elbow to avoid fatigue and decrease variability (cf. Wing, 1977a). However, participants differed in their preferred tapping style. The response key had a cushioned bottom contact and did not produce any audible sound unless it was struck rather hard. Participants were instructed to start tapping with the second tone in a sequence and to continue tapping at the same tempo after the sequence ended until a lower tone was heard. Nothing was mentioned about perturbations or changes in tempo. Although the changes in multiple IOIs approached the detection threshold for tempo changes obtained in some psychophysical studies (Drake & Botte, 1993; Friberg & Sundberg, 1995; McAuley & Kidd, 1998), none of the participants, when asked after the experiment, mentioned that they had noticed any changes in tempo or IOI duration within sequences. Thus, subjectively, the task was a simple synchronization-continuation tapping task. The three baseline tempi were discriminably different, of course. The five blocks of trials were presented twice so that each of the 21 sequences was presented 10 times.

Results and Discussion

Figure 2 presents the results in terms of intertap intervals (ITIs). The asynchronies during the synchronization phase were not of particular interest in the present context; for relevant discussions, see Thaut, Miller, et al. (1998) and Repp (in press). Figure 2a

shows the average ITIs for the isochronous sequences. The dotted horizontal lines without data points represent the sequence IOIs. The double standard error bars (roughly, 95% confidence intervals) illustrate the variability across participants. (Standard error bars are omitted in the other panels of the figure to avoid visual clutter; variability was similar in all conditions.) Several trends are independent of any perturbations in sequence timing and are visible in the other panels as well: (a) It took several taps (about three ITIs) to "tune in" to the correct tempo at the beginning of a sequence (cf. Fraisse, 1966; Semjen et al., 1998). (b) Tapping to slow sequences started out too slow, whereas tapping to fast sequences started out too fast, although there were considerable individual differences in that respect. (Note the large standard errors for the first ITI.) This finding is of some interest but is not directly relevant to the main purpose of the experiment; therefore, it is discussed in Appendix B. From the third ITI, the average ITIs were in close agreement with the sequence IOIs and varied little across participants, especially at the faster tempi. (c) The first continuation ITI tended to be lengthened, especially in the slower sequences and apparently as a reaction to the sudden end of the sequence.[5] (d) The subsequent ITIs were generally close to the baseline tempo established by the sequence IOIs, although there were some individual tempo biases that account for the observed variability.

The other panels of Figure 2 compare perturbation conditions with positive and negative Δt values (i.e., 10-ms increments and decrements in IOI duration). By focusing on this contrast, the isochronous baseline and any tempo biases in continuation tapping may be disregarded. Figure 2b shows the results for a single changed IOI at the end of the tone sequence. The sequence IOIs are again indicated by the dotted lines that now bifurcate at the end because of the contrasting changes in the final IOI. The sequence-final change in IOI duration was echoed in the immediately following ITI. This seems like a period correction because the observable tapping period (the ITI) has adapted to the sequence period (the IOI). However, the ITIs during continuation tapping were not affected by the stimulus perturbation. This suggests that the change in a single IOI had no effect on the underlying time-keeper period and that the observed ITI adjustment was, in fact, a pure phase correction (cf. Semjen et al., 1998; Vorberg & Wing, 1996).

Figure 2c shows the results for three changed IOIs. A rapid adaptation of the ITIs to the new IOIs can be seen after a lag of one position. This adaptation persisted to some extent, but not fully, during the subsequent continuation ITIs, suggesting partial period

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[4] 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 paper, all stimulus specifications and results are reported as they appeared in MAX. Apart from the constant scaling factor, MAX was highly accurate (within 1 ms) in timing the sequences and registering the keypresses.

[5] The ITI in Position 10 of the synchronization phase is the interval between the last tap that coincided with a tone and the first tap that did not. This ITI was considered to belong to the synchronization phase because the participants did not yet know that the sequence had ended (unless they had counted, which generally seemed to not have been the case).
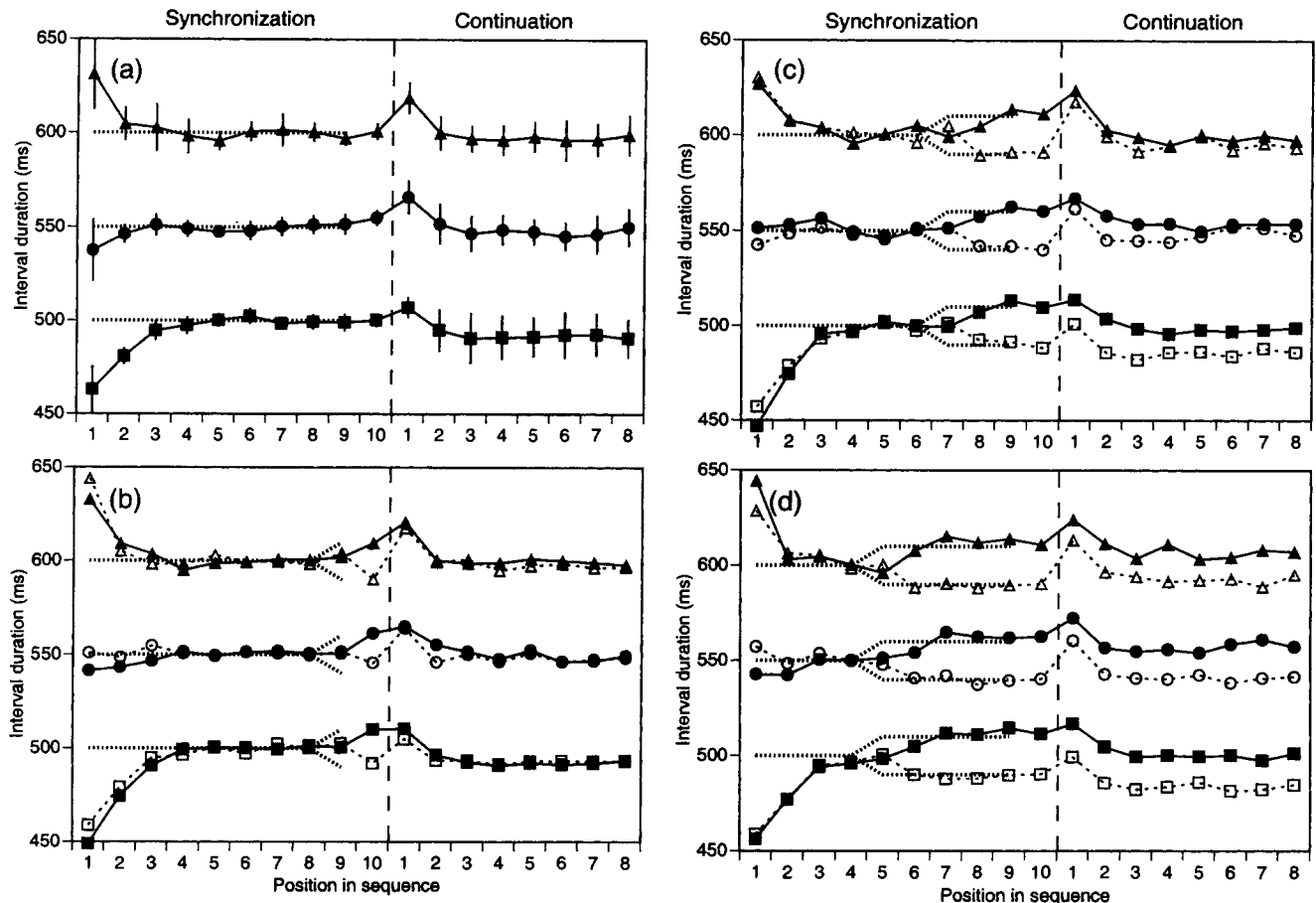
Figure 2. Average intertap intervals (ITIs) during synchronization and continuation phases in Experiment 1, for three sequence baseline interonset interval (IOI) durations. The heavy dotted lines represent the sequence IOIs. (a) Isochronous condition. Double standard error bars illustrate the variability across participants, which was similar in all conditions (roughly, 95% confidence intervals). (b) One changed IOI. (c) Three changed IOIs. (d) Five changed IOIs. In Panels b–d, the heavy line with filled symbols represents the ITIs in the IOI increment condition ($\Delta t = +10$ ms), whereas the dashed line with open symbols represents the ITIs in the IOI decrement condition ($\Delta t = -10$ ms).

correction. The magnitude of this lasting effect was largest at the fast tempo and smallest at the slow tempo.

Figure 2d shows the results for five changed IOIs. Following the tempo adaptation during synchronization, a lasting effect on continuation tempo can be seen at all three sequence tempi though the effect was still smaller than the difference between the positive and negative Δt values (i.e., 20 ms), which indicated incomplete period correction.

To determine the statistical significance of these findings, I first conducted an overall repeated measures analysis of variance (ANOVA) on the continuation ITIs. The completely isochronous condition was not included. The baseline IOI duration was subtracted from all ITIs to eliminate the trivial main effect of tempo. The variables in the ANOVA were number of changed IOIs (1, 3, or 5), direction of change (negative or positive), tempo (fast, medium, or slow), and position (1–8). The grand mean, $F(1, 7) = 0.09$, and the main effect of tempo, $F(2, 14) = 2.4, p < .13$, were not significantly different from zero, which means that there was no significant overall bias to deviate from the baseline tempo

during continuation tapping. The main effect of position, however, was highly significant, $F(7, 49) = 15.3, p < .0001$. This was due to the lengthening of the first continuation ITI, noted earlier. When that ITI was omitted, the main effect of position was no longer significant, $F(6, 42) = 1.3, p < .28$. At the same time, the grand mean and tempo main effects remained nonsignificant, indicating that the lengthening of the initial ITI did not mask a significant tendency to deviate from the baseline tempo in the opposite direction.

The effects of primary interest were the main effect of direction, $F(1, 7) = 142, p < .0001$, which confirmed that perturbations of opposite sign had divergent effects on the ITIs and especially the Number × Direction interaction, $F(2, 14) = 29.5, p < .0001$, which indicated that the effect of the perturbations on continuation tapping increased with the number of changed IOIs. In addition, the Direction × Position interaction approached significance, $F(7, 49) = 2.2, p < .06$, while the Number × Direction × Position interaction, $F(14, 98) = 2.1, p < .02$, and the Tempo × Number × Position interaction, $F(28, 196) = 1.6, p < .03$, passed the con-

ventional significance criterion. These interactions remained significant when the first ITI was omitted from the analysis.

To unpack these interactions, I conducted separate ANOVAs on the data for each number condition. The position main effect was highly significant in all three analyses and is of no further interest. For changes of a single IOI (Figure 2b), no other effect reached significance. In particular, the main effect of direction fell short of significance, $F(1, 7) = 4.0, p < .09$. This confirms that the tempo of continuation tapping was essentially unaffected by a single changed IOI. By contrast, for changes of five IOIs (Figure 2d), the main effect of direction was highly significant, $F(1, 7) = 243, p < .0001$. Only one other effect reached significance in this condition, which was the Direction × Position interaction, $F(7, 49) = 2.3, p < .05$, which seemed spurious. The results for changes of three IOIs (Figure 2c) were more complex. Here, the significant effects included not only the main effect of direction, $F(1, 7) = 18.6, p < .004$, but also the Direction × Tempo interaction, $F(2, 14) = 9.2, p < .003$, the Direction × Position interaction, $F(7, 49) = 3.3, p < .007$, and the Tempo × Position interaction, $F(14, 98) = 3.2, p < .0003$. These respective interactions reflect the findings that the tempo of continuation tapping was more affected when the baseline tempo was fast than when it was slow, that this effect diminished somewhat over time, and that the lengthening of the first ITI was more pronounced at a slow than at a fast tempo (cf. Figure 2c).

The preceding ANOVAs did not include the isochronous condition, which seemed superfluous. There was one additional issue, however, that a comparison with the isochronous condition could shed some light on, namely whether IOI increments and decrements had symmetric effects on continuation tapping. To that end, I repeated the overall ANOVA after subtracting the continuation ITIs of the isochronous condition from the continuation ITIs of the perturbed conditions at the same baseline tempo. In addition, the sign of the data was reversed for the IOI decrement conditions, in order to compare the IOI increment and decrement conditions with regard to the absolute deviations of the ITIs from the isochronous baseline. The main effect of direction, which would have reflected any asymmetry between the effects of IOI increments and decrements on continuation ITIs, was nonsignificant both in the overall ANOVA, $F(1, 7) = 1.39, p < .28$, and in subsequent separate ANOVAs on the conditions with different numbers of changed IOIs. The effects that were significant were analogous to those found in the earlier analyses. Thus, there was no evidence for any asymmetry in the effects of positive and negative perturbations.

Figure 3 presents a summary of the results in terms of the differences between the ITIs for corresponding IOI increment and decrement conditions (Figure 2b–d), starting with the ITI following the first changed IOI and averaged over the three baseline tempi. The maximal expected difference was 20 ms. What is of primary interest is the ITI adaptation during the synchronization phase, which was about 75–85% of the expected maximum in the first ITI after a perturbation and more than 100% in the following ITIs (when three or five IOIs were changed). This overcompensation probably reflects the simultaneous engagement of phase correction and period correction processes. Indeed, substantial initial overcompensation is the norm when step changes are large enough to be readily detectable (Michon, 1967; Repp, in press; Thaut, Miller, et al., 1998). The present multiple IOI changes were in the vicinity of the detection threshold (Drake & Botte, 1993; Friberg & Sundberg, 1995), hence the incipient overcompensation.

Quick adaptation of ITIs during synchronization in combination with slow adaptation of asynchronies (not discussed here) led Thaut, Miller, et al. (1998) to the conclusion that period adaptation takes priority over phase adaptation when step changes are small (i.e., subliminal). Although this is an accurate description of the observable behavior (adaptation), the present results suggest that just the opposite is the case in terms of the hypothetical underlying processes (correction): The observable rapid period adaptation seems to be due to phase correction, at least initially, whereas the observable slow phase adaptation (Repp, in press; Thaut, Miller, et al., 1998) is likely to be due to slow period correction. (Note that both underlying processes affect both ITIs and asynchronies; see Appendix A.) The initial time course of the internal timekeeper period correction in response to a small change in tempo, as roughly suggested by the present continuation tapping data, is portrayed in Figure 4. The ITI differences between corresponding IOI increment and decrement conditions are expressed here as a percentage of the maximal expected difference (20 ms) and are shown as a function of the number of changed IOIs, separately for each baseline tempo. It is evident that even after five changed IOIs, the internal period had adjusted to only about 75% of the change. After three changed IOIs, timekeeper period correction was more effective at the fast tempo than at the other two tempi, a difference that suggests a role of relative rather than absolute Δt. After a single changed IOI, there was hardly any effect on the timekeeper period. This last finding is considered the main result of Experiment 2 for the present purposes because it pertains to the earlier studies of Repp (2000a) and to the following experiments, which examined compensation for subliminal pulse changes (i.e., single changed IOIs) with a baseline IOI of 500 ms. It may now be safely assumed that such perturbations elicit only a phase correction.

The following experiments continued the investigation of compensation for subliminal pulse changes by asking a new question: Given that these perturbations elicit a phase correction, and given that the asynchronies between tones and taps provide the informa-
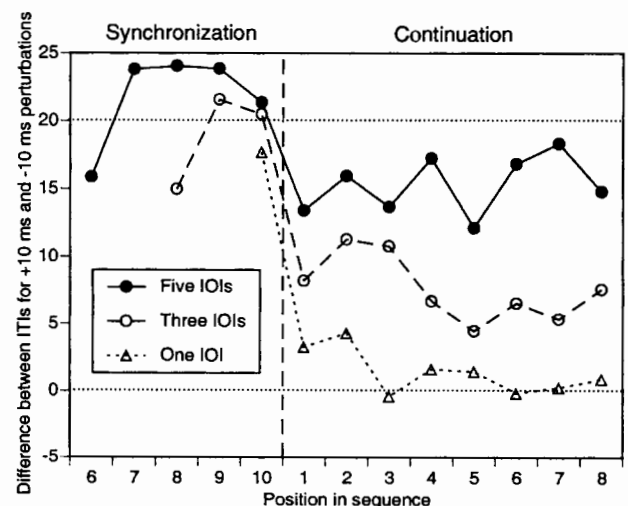

Figure 3. Average difference between the intertap intervals (ITIs) in the interonset interval (IOI) increment and decrement conditions (for +10 and −10 perturbations) in Experiment 1, shown separately according to the number of changed IOIs.
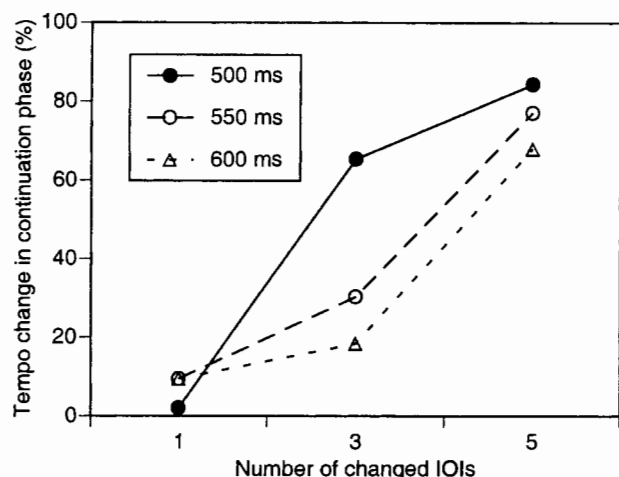
Figure 4. Average tempo change during the continuation phase of Experiment 1, expressed as a percentage of the maximal expected change, for each of three baseline tempi as a function of the number of changed interonset intervals (IOIs).

tion on which phase correction is based, are these sensorimotor asynchronies then crucial for effective phase correction to occur? In ordinary synchronization, in which the taps are more or less in phase with the tones, the asynchronies are relatively small and vary around a point of perceived simultaneity of tap and tone, which corresponds to a small negative asynchrony. Experiments 2–5 examined whether phase correction occurs when the sensorimotor asynchronies are much larger and vary around a point of perceived nonsimultaneity or when they are absent altogether. The results of these studies were expected to yield new information bearing on the nature of the processes underlying error correction in synchronization.

Experiment 2

Repp (2000a) demonstrated that complete compensation for subliminal pulse changes occurs within 2–3 taps when the taps are intended to be in phase with the tones. The question asked in Experiment 2 was whether similarly rapid and complete phase correction would occur in antiphase tapping. Sensorimotor asynchronies are large in antiphase tapping: They vary around a value of approximately half the sequence IOI because the taps occur approximately halfway between the tones. If phase correction is always based on sensorimotor asynchronies, then the asynchronies must be compared against an internal reference value equivalent to half the sequence IOI (here, 250 ms). Phase correction based on this comparison may well be less effective than phase correction in inphase tapping because it may be more difficult to register deviations from such a long interval (a clear successiveness of tap and tone) than from zero (subjective simultaneity).

Another way of conceptualizing antiphase tapping that is more in line with dynamic systems approaches would be to hypothesize separate perceptual and motor timekeeping processes that are coupled to each other. In that case, an attentional oscillator (Large & Jones, 1999), which is entrained by the tone sequence and predicts the time of occurrence of upcoming tones, would register

the perturbation (a sensoricognitive asynchrony, as it were) and communicate it to a motor timekeeper that has the same period but the opposite phase. This model, too, would seem to predict less effective phase correction in antiphase than in inphase tapping because two oscillators in antiphase are likely to be less tightly coupled and hence less effective communicators.

A third way of conceptualizing antiphase tapping is that cognitive subdivision of sequence IOIs occurs, resulting in two hierarchically nested timekeeping processes whose periods are in 2:1 ratio. The slower timekeeper would be an attentional oscillator that tracks the sequence tones, whereas the faster timekeeper would in addition define the time points at which taps are intended to occur. This would make possible the registration of an asynchrony between the predicted midpoint of an IOI and the time of occurrence of a tap (i.e., a cognitive–motor asynchrony). Note that phase correction based on this kind of asynchrony would be delayed because a perturbation could be registered only with the first tap following the perturbation.

Finally, it could be that cognitive subdivision occurs, but that the perturbation is registered as a sensoricognitive asynchrony by the faster attentional oscillator, which is tightly coupled both to the slower attentional oscillator and to the motor timekeeper (if there is such a separate process at all in that case). This would effectively communicate the perturbation to the motor system and enable phase correction on the first subsequent tap. At present, it is not known whether an attentional oscillator can actually register a subliminal deviation from a temporal expectation and communicate it effectively to the motor control system. A finding of effective phase correction in antiphase tapping might constitute evidence for this interesting possibility, though less effective phase correction in antiphase than in inphase tapping would not be incompatible with the hypothesis.

Several previous studies have investigated antiphase tapping, also called offbeat or syncopated tapping. Fraisse and Ehrlich (1955) noted that this task is difficult for untrained participants when the sequence IOIs are less than 1 s, because of a tendency to phase drift or even revert to inphase tapping. Kelso, DelColle, and Schöner (1990) made similar observations in a finger-wiggling task and analyzed the results in terms of dynamic systems concepts such as instabilities and phase transitions. (See also Volman & Geuze, 2000, who tested children.) However, Vos and Helsper (1992), who used practiced participants, found that the variability of antiphase tapping was only slightly larger than that of inphase tapping for IOI durations between 300 and 3,000 ms. They also investigated how effectively step changes in IOI duration were adjusted to and found equally rapid compensation in inphase and antiphase conditions. However, these step changes were supraliminal (5%, 20%, or 40%, with the results for the 5% condition being not very clear). Thus, the compensation probably represented deliberate period correction in response to perceived changes in sequence tempo rather than (or in addition to) phase correction based on asynchronies.

Semjen, Schulze, and Vorberg (1992) analyzed a variety of isochronous tapping conditions with sequence IOI durations of 400 and 600 ms. They found that, at the 600-ms IOI, the asynchronies were less variable in antiphase than in inphase tapping; in fact, the antiphase tapping variability was similar to that of tapping at twice the rate of the sequence (2:1 tapping). Because variability is known to decrease as ITI duration decreases, these results suggested to

Semjen et al. that antiphase tapping was governed by an internal timekeeper running at a rate twice as fast as that of the stimulus sequence. In other words, the stimulus intervals were cognitively subdivided and antiphase tapping amounted to tapping on every other beat of the faster cognitive timekeeper. When the sequence IOI was 400 ms, however, antiphase tapping was considerably more variable than inphase tapping. Thus, cognitive subdivision was no longer possible or beneficial at that rate, which is in agreement with many other results suggesting a discontinuity in the relationship between IOI duration, accuracy of timing control, and accuracy of time perception, somewhere between 200 and 300 ms (see, e.g., Friberg & Sundberg, 1995; Hibi, 1983; Peters, 1989). Below this limit, events apparently cannot be controlled or predicted individually; this means that obligatory grouping of adjacent events occurs. The baseline IOI employed in Experiment 2 (500 ms), chosen to match that of my earlier experiments (Repp, 2000a), was halfway between the values employed by Semjen et al. (1992) so that not much difference between the variabilities of inphase and antiphase tapping was expected (for practiced tappers).

Recently, Pressing (1998) compared the accuracy of an expert and a novice tapper in a variety of tasks, including antiphase and 2:1 tapping. Simple inphase tapping data for comparison came from a previous study by Pressing & Jolley-Rogers (1997). For sequence IOIs of 1,000 ms and 750 ms, antiphase tapping variability was about the same as or smaller than 2:1 tapping variability, but at IOIs of 375 ms (which only the expert could handle), antiphase tapping was much more variable than 2:1 tapping, in agreement with the findings of Semjen et al. (1992). Important for the present study is the fact that Pressing (1998) fitted a linear phase error correction model to his data and estimated the slope parameter that represents the effectiveness of the compensation. He found that the parameter value for antiphase tapping was equal to or even larger than that for inphase tapping and that the two subintervals of 2:1 tapping showed about equal parameter values. Pressing (1998) concluded that "error correction operates with equal efficiency at both cycle positions, regardless of the presence of a tone at that position" (p. 29). Because all sequences were isochronous, the asynchronies were due to the uncontrolled variability of the taps and, hence, were largely or entirely subliminal (cf. Repp, 2000a, Experiment 2). Experiment 2 may be seen as an attempt to replicate Pressing's findings with a different method, that of introducing systematic subliminal timing perturbations in the stimulus sequence.

Method

Participants. The participants were the same as in Experiment 1.

Stimuli. The stimulus sequences were a subset of those used by Repp (2000a, Experiment 1) in an inphase tapping task. Each sequence consisted of 50 high-pitched digital piano tones (C_8), with a baseline IOI of 500 ms. Four of the IOIs were different from the baseline duration (i.e., they represented pulse changes; see Figure 1a) and were separated from each other by nine baseline IOIs. This regular spacing greatly facilitated data analysis and was not expected to affect the results because the perturbations were generally not detectable. Four different perturbation magnitudes (Δt values) were used: -10, -6, $+6$, and $+10$ ms. The average detection threshold for such pulse changes tends to be above ± 20 ms (Friberg & Sundberg, 1995; Repp, 2000a, Experiment 5), and none of the participants reported hearing any irregularities in the timing of the sequences. For each

of the four Δt values, there were 10 sequences (trials), with Δt constant within a sequence. The positions of the perturbations were varied across the 10 trials such that the first perturbation occurred in the 6th sequence position in the first trial, in the 7th sequence position in the second trial, and so on. Thus, there were 40 different sequences that were arranged into four blocks of 10. The first two blocks contained pulse changes of ± 10 ms and the following two blocks contained changes of ± 6 ms. Positive and negative changes alternated from trial to trial within each block. The trials were in random order with regard to the positions of the perturbations.

Procedure. The response device, a white key on a Fatar Studio 37 MIDI controller, was the same as in Experiment 1 and in Repp (2000a). However, my experience during pilot runs suggested that antiphase tapping at the required rate was very difficult with this silent key; there was a strong tendency to synchronize with the tones in the sequence. The task was made easier when the response key produced a tone because an auditory criterion could be employed in maintaining a steady rhythm. (Previous antiphase tapping studies seem to have used keys that made a sound.) This made it advisable to also include a partial replication of an earlier inphase tapping experiment (Repp, 2000a, Experiment 1) with the additional auditory feedback. The MAX patch controlling the experiment registered the key depressions from the MIDI controller and generated the feedback tones on the Roland RD-250s digital piano, on which the tone sequences were also played back. The feedback tones were three semitones lower and had a constant lower intensity (MIDI key velocity of 30) than the stimulus sequence tones (MIDI key velocity of 60), regardless of the actual response key velocity. The intensity difference (roughly 10 dB) was introduced to prevent a possible but undesirable cognitive strategy in which the feedback tones are regarded as primary (metrically strong) and the sequence tones as secondary (metrically weak); the opposite strategy is considered the norm in antiphase tapping.

Another methodological consideration concerned the fact that the response key had a fairly large displacement (about 10 mm) with a soft bottom contact but a harder top contact. This potentially invited a strategy of synchronizing the top contacts (i.e., the upward finger excursions) with the sequence tones, thus converting antiphase to inphase tapping. Such a strategy (observed directly by Kelso et al., 1990, but not commented on in other previous antiphase tapping studies) was obviously undesirable. To discourage it, participants were instructed to oscillate the response key with their index finger without making any contacts. Because of the construction of the MIDI controller, the electronic registration of a key depression occurred about halfway through the downward movement of the key and could not be felt. To make the feedback tone coincide approximately with the lowest point of the key excursion, the tone was delayed by 20 ms. The participants (all were right-handed) were instructed to hold the MIDI controller on their lap, rest their right hand on their thigh, use the right index finger to oscillate the response key, and start tapping (i.e., oscillating) with the second tone in each sequence.

The experimental session was divided into two conditions, the first requiring inphase tapping and the second requiring antiphase tapping. The order of conditions, blocks, and stimulus sequences was the same for all participants. Counterbalancing was not used in order to give the benefit of practice to the more fragile conditions, namely the antiphase condition and the smaller Δt conditions within the inphase and antiphase conditions. At the beginning of each condition, a few practice trials were given until the participant felt comfortable with the task. Short breaks occurred between successive blocks and an optional longer break occurred between conditions. The session lasted about 1 hr.

Data analysis. Four contiguous episodes comprising 10 key depression times each were extracted from the data of each trial. Each episode began three positions before a perturbation point (P)—the tone onset terminating a changed IOI—and ended six positions after P. The remaining taps at the beginning and end of a trial were disregarded. Asynchronies for inphase taps were computed by subtracting the tone onset times from the registered key depression times. (Both times had been recorded relative to

the beginning of the sequence.) Asynchronies for antiphase taps were calculated relative to a time point 250 ms before the next tone onset. This procedure made antiphase asynchronies easier to compare with inphase asynchronies because they were in the same range, and in both conditions the tap linked to the tone onset in position P could not yet have been affected by the perturbation. A constant of 20 ms, representing the delay of the auditory feedback tone, was added to all asynchronies so that they reflected the relative timing of the feedback tones and not that of the electronic response key contacts (which occurred during the key trajectory).

Results and Discussion

The grand average asynchrony, derived from the three preperturbation (pre-P) positions, was -12 ms in inphase tapping and -10 ms (i.e., -260 ms) in antiphase tapping, a nonsignificant difference. Thus, the degree of anticipation of the IOI midpoints in antiphase tapping was very similar to that of the tone onsets in inphase tapping. However, it was clearly smaller than the anticipation tendency some of the same participants exhibited in earlier inphase tapping experiments in which the response key was silent (Repp, 2000a; see also Experiment 4 below), even if the 20-ms adjustment for the delay of the feedback tone was taken into account. This difference may be attributed to the availability of a within-modality (auditory) criterion of synchronization as well as possibly to a difference in finger kinematics—full key depression and release versus key oscillation (cf. Aschersleben & Prinz, 1995; Fraisse, Oléron, & Paillard, 1958). The average between-trial standard deviation of the asynchronies (calculated across the 10 trials for each sequence position within each Δt condition and then averaged across all positions, Δt conditions, and participants) was 18.6 ms in inphase tapping and 17.7 ms in antiphase tapping, again a nonsignificant difference. Although practice may have contributed to reducing variability in the antiphase condition, it is clear that antiphase tapping at this rate was not particularly difficult for most of the participants, in agreement with Pressing (1998) and Vos and Helsper (1992). Four of the 8 participants showed reduced standard deviations in antiphase tapping, which is consistent with the deployment of a cognitive subdivision strategy in antiphase tapping (Semjen et al., 1992). However, the sequence IOI was just at the limit at which cognitive subdivision ceases to reduce variability (Semjen et al., 1992), which probably explains the absence of an overall significant difference.

To determine whether compensation for the perturbations occurred, I first conducted a repeated measures ANOVA on the 3 pre-P asynchronies in all episodes with the fixed variables of tapping condition (2), direction of perturbation (2), magnitude of perturbation (2), episode (4), and position (3). The rationale for this analysis was that, if compensation did not occur at all or was incomplete, there would be a progressive, relative phase shift within each trial as a result of successive pulse changes in the same direction (Δt), up to a maximum of $-3\Delta t$ after the first three perturbations. Such a shift would be reflected in a significant Direction $\times$ Episode interaction and perhaps higher interactions involving these variables, because asynchronies would shift in opposite directions for positive and negative Δt values. However, not a single main effect or interaction was significant in this ANOVA. This suggested that complete compensation occurred in all conditions.

To determine the average time course of the phase correction, I first relativized the asynchronies in each episode by subtracting the average of the 3 pre-P asynchronies from all 10 asynchronies in the episode, so that the average pre-P baseline was zero. These relative asynchronies, averaged across episodes, trials, and participants, are shown as compensation functions for the different Δt conditions in Figure 5a (inphase) and 5b (antiphase). The expected asynchrony in Position P was $-\Delta t$ in both conditions. The data met that expectation in that the obtained values were all within 2 standard errors of the expected values in all conditions. (Standard errors are not shown in Figure 5a and 5b to avoid visual clutter; but see Figure 5c.) Compensation was indicated by the return of the postperturbation (post-P) asynchronies to the pre-P baseline. The results were highly similar for the two tapping conditions and also to the data of Repp (2000a, Experiment 1) for inphase tapping on a silent response key. It should be noted that the tap in Position P + 1 occurred about 500 ms after the perturbed tone in the inphase condition, but only about 250 ms after the perturbed tone in the antiphase condition. Nevertheless, the amount of compensation observed was similar.

Three-way repeated measures ANOVAs were conducted on the relative asynchronies in Positions P to P + 3, separately for the two absolute Δt magnitudes (± 10 and ± 6 ms). The variables were tapping condition (2), direction of perturbation (2), and position (4).[6] The sign of the asynchronies for negative Δt was reversed to remove trivial interactions caused by the opposite direction of the compensation for positive and negative perturbations. In both analyses, the main effect of position was highly significant: for $\Delta t = \pm 10$ ms, $F(3, 21) = 47.3, p < .0001$, and for $\Delta t = \pm 6$ ms, $F(3, 21) = 20.6, p < .0001$. This reflects the fact that the relative asynchronies returned toward zero following a perturbation. No other effects reached significance. The Position $\times$ Condition approached significance in the analysis on $\Delta t = \pm 10$ ms, $F(3, 21) = 2.9, p < .06$. As seen in Figure 5b, however, this effect was not due to slower compensation in the antiphase condition but rather to a slight overshoot of the expected asynchronies in Position P in the inphase condition and a slight undershoot in the antiphase condition. This difference was probably spurious, as it was not present for $\Delta t = \pm 6$ ms.

A summary of the main findings appears in Figure 5c in a format that is also used in subsequent experiments. The average relative asynchronies in each position (shown in Figure 5a and 5b) were considered as a function of Δt, and the slopes of straight regression lines were calculated. These slopes are plotted in Figure 5c as a function of position with standard error bars reflecting the variability across participants. The expected slope in position P was -1 and the data were close to that value. The slope in position P + 1, if added to 1, gives an estimate of the effectiveness of compensation and a zero slope indicates that compensation is complete; that is, the asynchronies no longer show any influence of the perturbations. (Note that these slopes are independent of the transformation of absolute into relative asynchronies.) The results are in agreement with earlier findings (e.g., Pressing, 1998; Repp, 2000a; Semjen et al., 2000), suggesting about 50% compensation

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[6] The variable of episode (4) was averaged over because the analysis of the pre-P asynchronies had already indicated that compensation occurred throughout the trials.
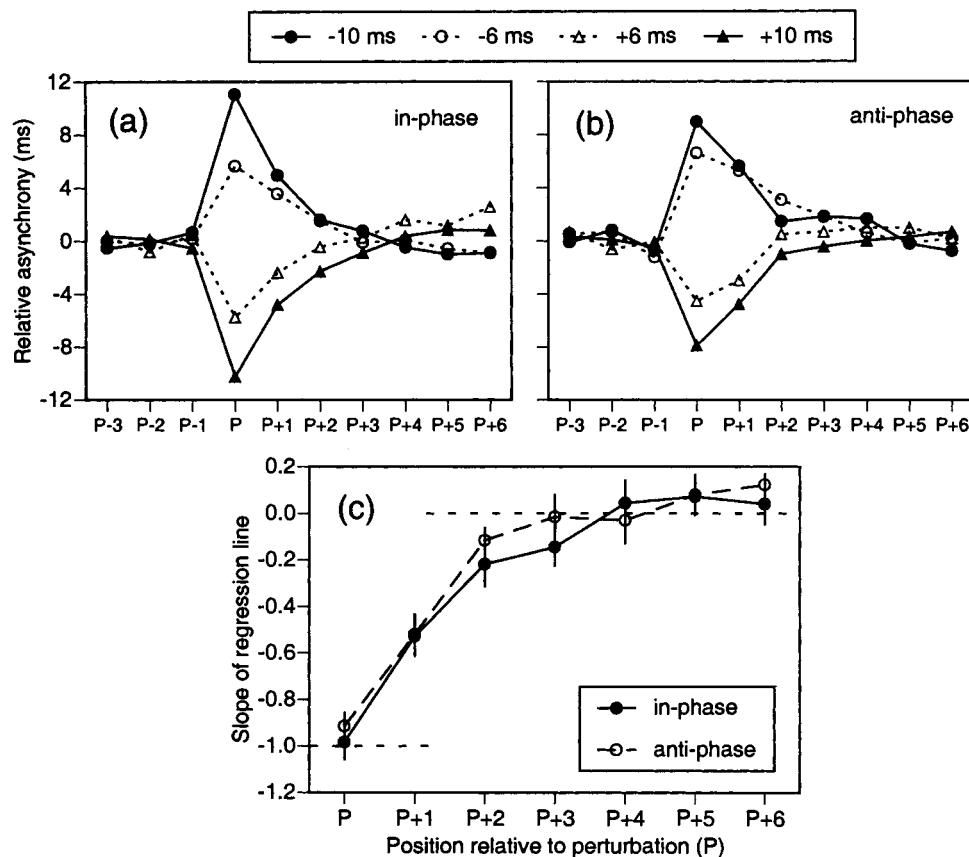
Figure 5. Average compensation functions for four sizes of Δt in Experiment 2. (a) Inphase tapping. (b) Antiphase tapping. (c) Slopes of regression lines relating average asynchronies to Δt, with standard error bars.

per tap at this sequence rate. Moreover, compensation in Position P + 1 was just as effective in antiphase tapping as in inphase tapping, even though the tap occurred 250 ms earlier in antiphase tapping. In other words, compensation was not delayed in antiphase tapping.

These results support arguments against several of the theoretical models outlined earlier. Coupled attentional and motor oscillators having the same period as the sequence should have resulted in less effective phase correction in antiphase tapping because of looser coupling in that condition. However, it could be argued that antiphase coupling is as strong as inphase coupling when an auditory rhythm can be monitored. The results also cast some doubt on the possibility that compensation in antiphase tapping is based on a comparison of sensorimotor asynchronies against an internal standard interval of 250 ms, because this again would have predicted less effective compensation in antiphase tapping. Certainly the results are inconsistent with the idea that the perturbation was detected by registering a cognitive-motor asynchrony because, in that case, the phase correction should have been delayed in the antiphase condition. The results seem most consistent with the hypothesis that participants used an attentional oscillator (Large & Jones, 1999) to register small deviations from expected times of occurrence. If so, then these results provide interesting evidence that not only subliminal sensorimotor asynchronies (Repp, 2000a) but also subliminal deviations from temporal expectancies (sen-

soricognitive asynchronies) can serve as sources of information for the temporal control of action. However, this conclusion remains tentative in view of the following considerations.

Experiment 3

With IOI durations of 500 ms, the only reasonable cognitive subdivision is bisection; smaller subdivisions are difficult or impossible because they fall within the zone of obligatory grouping of events. Also, oscillator-based models generally assume hierarchical nesting of coupled oscillator periods, which limits subdivision to simple integer ratios such as 1:2. This means that these models cannot easily account for tapping in phase relationships other than inphase or antiphase at a 500-ms sequence rate. Yet, this is not an impossible task, at least not for musically trained individuals. During informal explorations, I discovered that after only limited practice, I was able to oscillate my index finger quite consistently at either of two phase relationships other than inphase and antiphase, such that the tap-triggered tones either preceded the sequence tones (thus serving as upbeats) or followed them (thus functioning as downbeats with the sequence tones serving as upbeats). In each case, the tones formed what would be called a *dotted* rhythm in music, but without necessarily corresponding to any intended musical note values or exact ratios; the tones formed just the ratios that felt most comfortable and could be maintained

most easily. Research on interlimb coordination (e.g., Schöner, Zanone, & Kelso, 1992; Tuller & Kelso, 1989; Yamanishi, Kawato, & Suzuki, 1980; Zanone & Kelso, 1992, 1997) has demonstrated that arbitrary phase relationships can be produced and learned, albeit with increased variability and constant errors relative to inphase and antiphase conditions. My observations suggested that musically trained individuals might be able to tap at certain self-selected phase relationships without much task-specific training, though perhaps with increased variability and provided that the production of an auditory rhythm serves as the goal.

Accordingly, Experiment 3 investigated whether compensation for subliminal timing perturbations would occur in (what seemed to be) arbitrary-phase tapping and whether that compensation would be as rapid and complete as observed previously in inphase and antiphase tapping. If that were the case, the cognitive bisection model would have to be revised.

Method

Participants, stimuli, design, and procedure were the same as in Experiment 2. The only difference was that instead of inphase and antiphase tapping, dotted rhythms were asked for, such that the tap-triggered tones either preceded the sequence tones (upbeat condition) or followed the sequence tones (downbeat condition). The rhythms were described verbally ("tatah . . . tatah . . ."); no other auditory models or musical notations were provided. The participants were asked to find their own most comfortable rhythms. They were not explicitly discouraged from thinking of the rhythms in musical terms, but it was made clear that no specific musical rhythms were asked for. The only requirements were that the tap-triggered tones neither coincide with nor fall halfway between sequence tones and that the same rhythm be maintained throughout each task. The upbeat and downbeat rhythms did not have to be exactly the same. Participants started with the upbeat task, which seemed the easier one. In fact, one of the musically less-experienced participants felt unable to perform the downbeat task. As in Experiment 2, there were four blocks of 10 trials in each condition, with the two $\Delta t = \pm 10$ ms blocks preceding the two $\Delta t = \pm 6$ ms blocks.

As expected, the asynchronies in this experiment were a good deal more variable than in Experiment 2, and large phase drifts with subsequent corrections or even interruptions of tapping occurred occasionally, especially in the downbeat condition. Therefore, after extracting the 10-tap episodes from the data, only episodes whose asynchronies had a within-episode standard deviation of less than 20 ms were included in the analysis. For two of the musically less-experienced participants, the number of episodes that passed the criterion in the downbeat condition was considered too small for further analysis (less than 20% of the data). Therefore, there were usable data from only 5 participants in the downbeat condition.

Results and Discussion

Table 1 shows the percentages of episodes analyzed (there were 160 episodes per tapping condition), the mean raw asynchronies (but with 20 ms added to take into account the delay of the feedback tone), and the average between-episode standard deviations for the individual participants in the two conditions. The upbeat asynchronies are negative because the taps preceded the stimulus tones, whereas the downbeat asynchronies are positive. One participant (M1, the author) shifted strategy between blocks in the downbeat condition, as indicated in Table 1 by two different mean asynchrony values (75; 125); another participant (F4)

Table 1

Percentage of Episodes Used (n = 160), Mean Asynchrony (in Milliseconds), and Average Between-Episode Standard Deviations of Asynchronies (in Milliseconds) for Experiment 3

Participant	Upbeat condition			Downbeat condition		
	% used	Mean asy	SD	% used	Mean asy	SD
M1	93	−154	17	85	75; 125	20
M2	86	−165	19	89	186	16
M3	91	−210	17	76	207	17
M4	56	−153	20	—	—	—
F1	65	−172	19	16	(not analyzed)	
F2	41	−185	22	66	180	26
F3	65	−161	22	18	(not analyzed)	
F4	72	−172	20	34	149	40

Note. M = male, F = female; asy = asynchrony. M4 did not complete the downbeat condition.

showed very large variation between episodes in the downbeat condition. With these exceptions, the asynchronies showed satisfactory stability across the episodes that passed the selection criterion. Recently, Cummins and Port (1998) and Semjen and Ivry (2001) have provided evidence that, in addition to bisection, 2:1 or 1:2 division of an interval offers stability in rhythmic performance, albeit with longer IOIs than used here. This would correspond to asynchronies of ± 167 ms in the present case. It can be seen that some, but not all, of the observed average asynchronies were close to these values.

Relative asynchronies were again calculated by subtracting the average asynchronies in the three pre-P positions from all asynchronies in each episode.[7] The average compensation functions are shown in Figure 6a and 6b. The graphs show that compensation definitely occurred but at a slower rate than in Experiment 2, at least after Position P + 1. This can be seen more clearly in Figure 6c, which summarizes the results in terms of the slopes of regression lines relating asynchronies to Δt.

Separate three-way repeated measures ANOVAs were conducted on the $\Delta t = \pm 10$ ms and ± 6 ms data for Positions P to P + 3 after reversing the signs of the asynchronies for positive Δt, for the 5 participants whose data were complete. The independent variables were tapping condition (2), direction of perturbation (2), and position (4). The position main effect, which reflects the return of the post-P asynchronies toward zero, was significant for both magnitudes of Δt, $F(3, 12) = 19.3$ and $19.5, p < .0002$. In the $\Delta t = \pm 6$ ms analysis, there was also a significant main effect of condition, $F(1, 4) = 16.6, p < .05$, reflecting a positive phase drift in the downbeat condition, and a triple interaction between condition, direction, and position, $F(3, 12) = 3.6, p < .05$, that was mainly due to considerable undershoot of the expected asynchronies in Position P for $\Delta t = \pm 10$ ms in the downbeat condition (see Figure 6b); for a possible explanation, see below. In separate analyses of the upbeat and downbeat conditions, the position main effect was highly significant in the upbeat condition for both Δt: $\Delta t = \pm 10$ ms, $F(1, 7) = 27.2, p < .0001$; $\Delta t = \pm 6$ ms, $F(1, 7) = 10.6, p <$

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[7] Because of the data attrition that was due to screening of trials, the ANOVA on the pre-P asynchronies with episode as a variable was omitted.
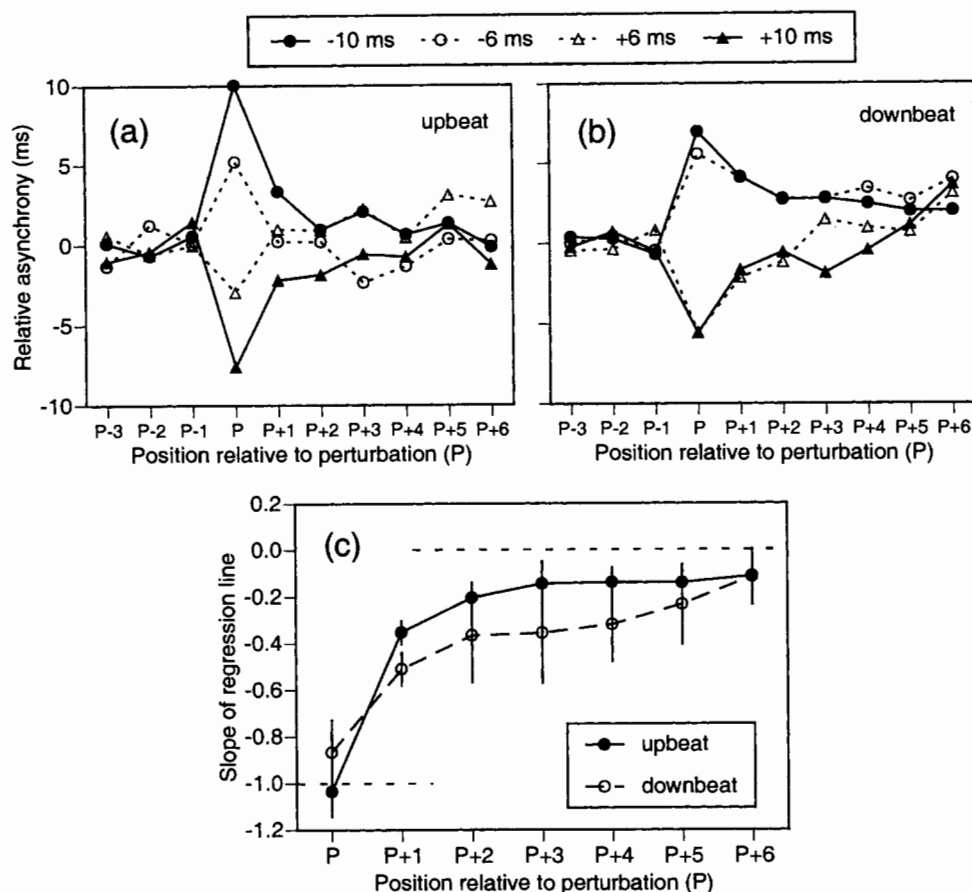
Figure 6. Average compensation functions for four sizes of Δt in Experiment 3. (a) Upbeat tapping (8 participants). (b) Downbeat tapping (5 participants). (c) Slopes of regression lines relating average asynchronies to Δt, with standard error bars.

.0003, and it did not interact with direction. In the downbeat condition, however, the position main effect fell short of significance for $\Delta t = \pm 10$ ms, $F(1, 4) = 3.2$, $p < .07$, and reached significance for only $\Delta t = \pm 6$ ms, $F(1, 4) = 4.6$, $p < .03$. Thus, there was less convincing evidence of compensation in the downbeat than in the upbeat condition, mainly because of the difficulty of the downbeat task and the consequent variability of the data (but note the further convergence toward the baseline that occurred over Position $P + 4$ to $P + 6$, which were not included in the ANOVAs).

Another factor that may have contributed to the weaker results in the downbeat condition is that participants may have already corrected for the perturbation on the immediately following tap. Note that this tap was considered here to occur in Position P, whereas in the antiphase tapping condition of Experiment 2 it was considered to occur in Position $P + 1$. In antiphase tapping, in which the next tap occurred about 250 ms after the perturbed tone, compensation was as strong as in inphase tapping. In the downbeat condition, the next tap occurred 75 to 207 ms after the perturbation (see Table 1). Thus, compensation could have occurred at the longer intervals within that range. This may account for the undershoot of the expected asynchronies in Position P. However, the data screening may also have introduced a bias in that direction.

On the whole, these results suggest that compensation for subliminal timing perturbations occurs regardless of the phase of the finger oscillations relative to the sequence of stimulus tones. This cannot be explained by a model of cognitive bisection or by hierarchical oscillators whose periods are in 2:1 relationship. A more flexible arrangement of timekeepers is required. Because compensation was not quite as effective in arbitrary-phase tapping as in inphase and antiphase tapping, the model postulating coupled perceptual and motor oscillators with equal periods could be resurrected to account for the data. Some participants' data may also be consistent with cognitive trisection, that is, nested attentional oscillators whose periods form a ratio of 3:1; but not all the individual data can be explained in this way. A more appealing explanation, however, is provided by the timing control model of Semjen and Ivry (2001). It suggests that more or less arbitrary target intervals, defined within the auditory modality as a rhythmic pattern, can be intended, produced, and monitored, though under constraints that favor simple ratios. In other words, a cognitive template of the intended rhythmic pattern serves as the reference and deviations from that reference are corrected by means of the phase correction mechanism. (It should be noted that the tasks of this experiment would have been impossible to perform with a silent response key.) The more or less arbitrary subdivisions may

then be nested within an attentional oscillator cycle that monitors the sequence tones and registers subliminal deviations that are forwarded to the motor control system.

Experiment 4

The results of Experiments 2 and 3 have encouraged the notion that subliminal deviations from cognitive temporal expectancies can inform motor control, though alternative accounts of the results have not been ruled out. Experiment 4 was intended to provide another test of the temporal expectancy hypothesis by investigating whether phase correction occurs in inphase tapping when the tap coinciding with a perturbed tone is omitted. Clearly, there is no sensorimotor asynchrony available in that case. Thus, if that asynchrony is important, phase correction should be delayed until after a tap has been made that yields such an asynchrony. (It makes little sense to think of the long interval between the preceding tap, which accompanies the preceding tone, and the perturbed tone as a relevant sensorimotor asynchrony.) By contrast, if phase correction were evident as soon as tapping resumes and if it resembled that observed in continuous inphase tapping, then there would be strong evidence that a perceptually registered (sensoricognitive) subliminal asynchrony can inform the motor control system.

Method

Participants. The participants were the same as in the preceding experiments.

Stimuli. The stimulus sequences were the same as in Experiments 2 and 3, except that the pitch of 12 of the 50 tones was changed from C_8 (MIDI pitch 108; 4168 Hz) to E_7 (MIDI pitch 100; 2638 Hz) in groups of three. These tones served as cues to stop tapping. Two sets of sequences were created. In the first set, referred to as the *P set*, the three tones immediately preceding Position P were lower in pitch. In the second set, referred to as the *P − 1 set*, the three tones immediately preceding Position P − 1 were lower in pitch.

Procedure. This experiment required two sessions, the first using the P set and the second using the P − 1 set of sequences. In each session, there were two conditions in fixed order. The first condition required participants to skip one tap after hearing three successive tones of lower pitch and then to resume tapping. The second condition required participants to skip two taps. In combination with the two types of sequences, these instructions
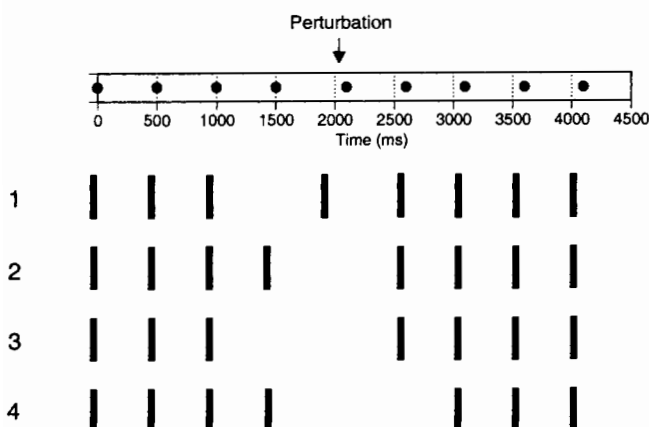

Figure 7. Schematic diagram of the four tapping conditions in Experiment 4. The size of the perturbation is exaggerated for visual effect.
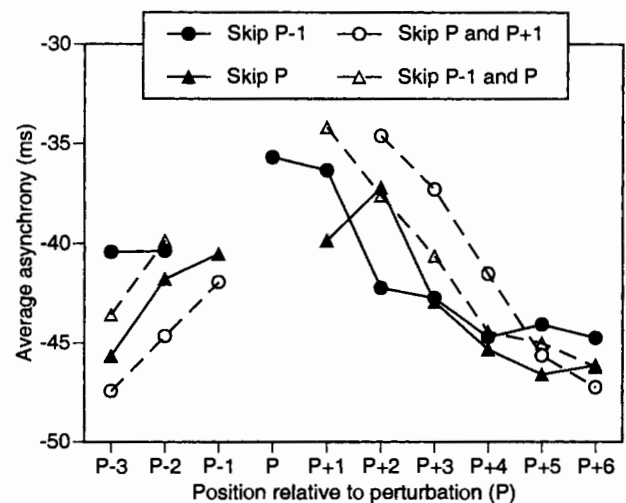

Figure 8. Average asynchronies in the vicinity of skipped taps in Experiment 4.

resulted in four conditions that are illustrated schematically in Figure 7: (1) skip P − 1; (2) skip P; (3) skip P − 1 and P; and (4) skip P and P + 1. The first condition was included to demonstrate that normal phase correction occurs when a tap coincides with the perturbed tone, even though the preceding tap is omitted and some sequence tones are lower in pitch. The other three conditions tested the hypothesis that compensation would occur in the absence of a sensorimotor asynchrony. The second condition provided the most straightforward test by deleting just the crucial sensorimotor asynchrony in Position P. The third condition was similar but the motor activity was disrupted for a longer time and the lower-pitch tones were more distant from P. In the fourth condition, tapping resumed later than in the second condition, which perhaps introduced a demand on memory. Each condition included four blocks of 10 trials each, with two $\Delta t = \pm 10$ ms blocks preceding two $\Delta t = \pm 6$ ms blocks, as in Experiments 2 and 3. However, the response key was silent now and was depressed and released fully, as in Experiment 1. Participants were instructed not to move their finger when they skipped a tap.

Results and Discussion

This experiment yielded several unexpected findings, which complicate the results but pose interesting challenges for models of error correction and synchronization. To begin with, omission of one or two taps had systematic effects on the timing of preceding and following taps, independent of any perturbations in the tone sequence. Figure 8 shows the raw within-episode asynchronies in the four tapping conditions, averaged across episodes and the four Δt values.[8] The magnitude of the overall anticipation tendency was similar to that obtained in earlier experiments using the silent

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[8] Any effects of the perturbations on tap timing were effectively averaged out here because the Δt values themselves added up to zero. Because previous studies had not shown a significant asymmetry in phase correction for positive and negative Δt values, there was no need to include perfectly isochronous sequences in the experiment to assess the effects shown in Figure 8. The phase correction in response to a perturbation was superimposed on (i.e., seemed additive with) the phase fluctuation that was due to skipping one or two taps. It seems unlikely that the pitch cue as such contributed to this fluctuation.

response key (Repp, 2000a). However, it is evident that the asynchronies decreased (i.e., became less negative, so the data points move up in the figure) before a tap was skipped and increased again afterward, with this trend being somewhat more pronounced when two taps were skipped rather than one. A repeated measures ANOVA was conducted on the asynchronies surrounding skipped taps with the following variables: location of first skipped tap (2), number of skipped taps (2), and position (8). The position variable included three asynchronies preceding and five following a skip, but not the skip itself.[9] The main effect of position was significant, $F(7, 49) = 4.0$, $p < .002$, as was the Number × Position interaction, $F(7, 49) = 2.3$, $p < .05$, confirming the impressions gained from Figure 8. A two-way ANOVA comparing the three asynchronies preceding and following a skip showed a significant main effect of the additional variable of before–after (2), $F(1, 7) = 7.4$, $p < .04$, because the asynchronies were less negative following a skip. The Before–After × Position (3) interaction fell short of significance, but the main effect of position was significant on preceding and following asynchronies separately, $F(2, 14) = 5.1$, $p < .03$, and $F(2, 14) = 4.0$, $p < .02$, indicating significant changes over positions. The relatively low significance levels reflect considerable individual differences in these trends, which were evidently due to the kinematics of stopping and continuing to tap as well as the preparation for this action during the pitch cue.

To determine whether compensation for the perturbations occurred, I carried out separate ANOVAs on the pre-P asynchronies in each of the four tapping conditions, with the variables of episode (4), direction of perturbation (2), magnitude of perturbation (2), and position in episode (3 or 2). As in Experiment 2, the rationale of these analyses was to determine whether asynchronies changed across episodes within sequences in a way that depended on the direction and magnitude of the perturbations. Unexpectedly, the main effect of episode was highly significant in all four analyses, $F(3, 21) > 6$, $p < .004$. It reflected an increased negativity of asynchronies following the first episode (an average difference of about −6 ms) with a slight change in the opposite direction thereafter. Apart from this general drift and some marginally significant effects that need not be discussed, there were interactions involving episode in the two conditions in which a single tap was skipped, but not in those in which two taps were skipped. Both single-skip conditions showed a significant Episode × Direction interaction, $F(3, 21) > 7.9$, $p < .001$, and a significant Direction × Magnitude interaction, $F(1, 7) > 12.6$, $p < .01$; one condition (skip P − 1) also showed a significant Episode × Direction × Magnitude interaction, $F(3, 21) = 6.9$, $p < .002$, and the other (skip P) a significant Episode × Magnitude interaction, $F(3, 21) = 3.1$, $p < .05$. These interactions are exactly the ones that would indicate incomplete compensation. However, inspection of the data revealed just the opposite pattern. Instead of shifting in the direction opposite to that of the perturbations, the asynchronies shifted in the same direction. This suggests some form of overcorrection resulting in a progressive phase shift. These results are shown graphically in Figure 9. The main effect of episode is evident in the increased negativity between Episodes 1 and 2 in all four panels, and the interactions in the single-skip conditions are due to the spreading apart

of the functions for different Δt values in Episodes 2–4 (Panels a and b). Note that this spread reflects the cumulative effects of only the first three perturbations in a sequence.

To examine the time course of compensation, I calculated double-relative asynchronies within each episode of each condition by first subtracting the average trend shown in Figure 8, and then subtracting the average of the three or two pre-P asynchronies from all asynchronies, so that the pre-P baseline was zero. The resulting average compensation functions are shown in Figure 10a–d, and the corresponding linear regression slopes are plotted in Figure 10e. Figures 10a and 10e (filled circles) show that phase correction following the omission of a tap in Position P − 1 was more rapid than in continuous inphase tapping (see Figure 5c). Instead of reaching an asymptote at the zero baseline, the asynchronies overshot the baseline at P + 2 and did not return to it within the following four taps, which caused the progressive phase shift shown in Figure 9a. A repeated measures ANOVA on the relative asynchronies from P to P + 6 with the variables of direction of perturbation (2), magnitude of perturbation (2), and position (7) showed a highly significant Direction × Position interaction, $F(6, 42) = 52$, $p < .0001$ that was due to the crossover of the compensation functions (Figure 10a). However, a separate analysis on positions P + 2 to P + 6 yielded no significant effects; even the main effect of direction fell short of significance, $F(1, 7) = 4.2$, $p < .09$.[10] Thus, the overcorrection visible in Figures 10a and 10e was not quite reliable statistically although the resulting progressive phase shift throughout the stimulus sequence (Figure 9a) was significant.

Figures 10b and 10e (unfilled circles) show the results of the condition in which the single tap coinciding with the perturbed tone was omitted. Interestingly, there was no evidence of gradual phase correction; that is, there was no negative relationship between relative asynchronies and Δt when tapping resumed. Instead, the relative asynchronies immediately showed a positive relationship with the perturbations that indicated overcompensation and persisted in the following positions. The main effect of direction was significant in an ANOVA on Positions P + 1 to P + 6, $F(1, 7) = 17.5$, $p < .005$, as was the Direction × Magnitude interaction, $F(1, 7) = 10.4$, $p < .02$, which reflects the opposite effects of absolute perturbation magnitudes for positive and negative Δt values. Although it seems in Figure 10b that the magnitude effect disappeared over positions, the relevant interaction was not significant. However, the positive effect of the perturbations persisted and resulted in a progressive phase shift throughout the sequence (Figure 9b).

The condition in which the taps in Positions P − 1 and P were omitted (Figures 10c and 10e; filled triangles) showed no effect of the perturbations at all. In other words, phase correction was

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[9] In the two conditions with only two pre-P asynchronies, the first pre-P asynchrony was taken to be the one in Position P + 6.

[10] This was due to one participant (myself) who showed a difference in the opposite direction (i.e., undercompensation). My phase correction process happens to be unusually slow, as observed in earlier experiments (Repp, 2000a) as well. This may be an effect of age, as I was the oldest participant.
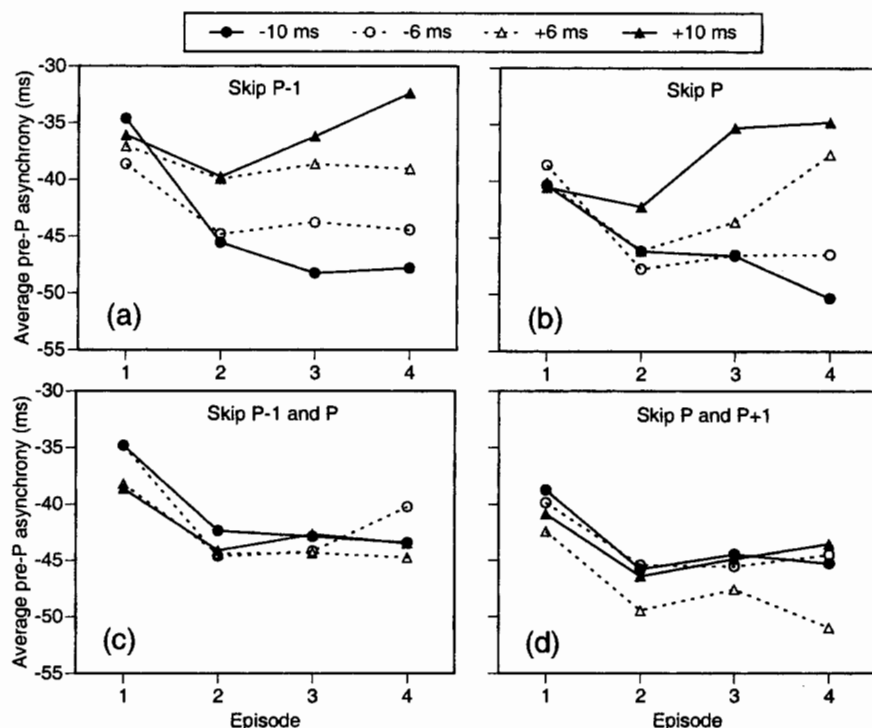
Figure 9. Average preperturbation (pre-P) asynchronies as a function of Δ*t* and episode in the four tapping conditions of Experiment 4. (a) Skip tap at P − 1. (b) Skip tap at P. (c) Skip taps at P − 1 and P. (d) Skip taps at P and P + 1.

complete in Position P + 1. There was no significant effect in the ANOVA.

The condition in which the taps in Positions P and P + 1 were omitted (Figures 10d and 10e; diamonds connected by dashed line) likewise showed no clear effect of the perturbations, although there were some significant effects in the ANOVA. They included a main effect of magnitude, $F(1, 7) = 7.3$, $p < .03$, but not of direction, a Direction × Magnitude interaction, $F(1, 7) = 7.8$, $p < .03$, and also a Magnitude × Position interaction, $F(4, 28) = 3.3$, $p < .03$. These effects are difficult to make sense of; they suggest some systematic changes between trial blocks because the magnitude factor was blocked.

Despite some complexities, these results clearly demonstrate that phase correction does occur in the absence of a sensorimotor asynchrony conveying the perturbation. In fact, phase correction seems to be more rapid when such an asynchrony is unavailable than when it is available. When a tap coincided with the perturbed tone, there was still an effect of the perturbation in Position P + 1, although it seemed smaller than the effect during continuous inphase tapping (Figure 5c). When the tap coinciding with the perturbed tone was skipped, however, there was perfect phase correction or even overcorrection in Position P + 1. This is difficult to explain by merely assuming than an attentional oscillator registers the perturbation in the absence of a tap because the time course of phase correction should be similar to that which occurs during continuous inphase tapping. Some additional factor must be playing a role. That factor is most likely the interruption of the continuous motor activity. (It seems unlikely that the lower

pitch of the preceding tones had any direct effect on tap timing.) What may be happening in that case is that *phase resetting* occurs with respect to the last tone. This process was proposed by Hary and Moore (1985, 1987), who believed it to play an intermittent role in continuous tapping as well. If the first tap after the interruption is timed relative to the perturbed tone and not relative to the last tap before the interruption, then any perturbation would be compensated for automatically and completely. If this is what occurred, then these results do not provide further evidence for registration of subliminal perturbations by an attentional oscillator.

However, this phase resetting strategy cannot account for the perturbation-dependent phase shifts in the conditions in which a single tap was skipped. This result suggests that an error-correction process that was based on a perceptually registered asynchrony operated in addition to phase resetting, thus causing the apparent overcorrection. But why was that overcorrection not corrected on subsequent taps? If it had been a phase correction that was added to the phase resetting, a subsequent return to the baseline should have been observed. Moreover, it seems a logical contradiction that phase resetting and phase correction would occur simultaneously. This leads to the possibility that period correction was involved in addition to phase resetting. Indeed, an extended phase shift has been observed by Thaut, Miller, et al. (1998) and Repp (in press) following subliminal step (tempo) changes in a sequence. I attributed this to incomplete period correction. If, in the present paradigm, the timekeeper period had been adjusted slightly in the direction of the lengthened or shortened IOI in the sequence (the pulse change), this would have led to the observed overcorrection.
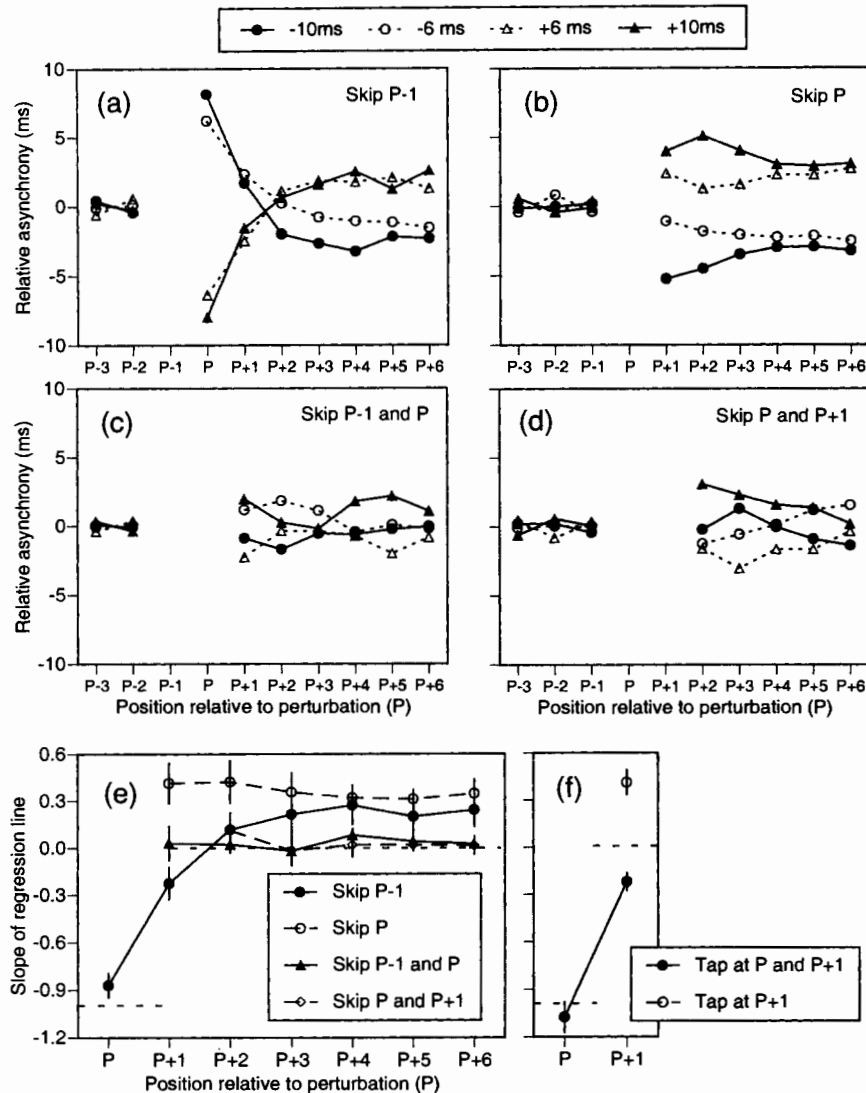
Figure 10. Average compensation functions for four sizes of Δ*t* in the four tapping conditions of Experiment 4. (a) Skip tap at P − 1. (b) Skip tap at P. (c) Skip taps at P − 1 and P. (d) Skip taps at P and P + 1. (e) Slopes of regression lines relating average asynchronies to Δ*t*, with standard error bars. (f) Results of Experiment 5. P = perturbation.

However, the results of Experiment 1 suggested that period correction is minimal after a subliminal pulse change. Perhaps it was the interruption of the continuous motor activity that led to more rapid period correction, in addition to phase resetting. In ordinary, uninterrupted tapping, it may be the continuity and inertia of the motor activity that prevents immediate phase and period correction, because of a tendency to maintain the current phase and, especially, the current period. When the continuity is disrupted and the inertia is removed, more rapid adjustments of phase and period may become possible.

These arguments move toward an explanation of the observed phase shifts, but the explanation is not yet complete. Why did the phase shifts occur only when a single tap was skipped, and why did they occur regardless of whether that tap coincided with the perturbed tone? A period resetting account would predict maximal

period adjustment when tapping is resumed immediately after the pulse change (Figure 9b and 9c), a smaller effect when tapping continues after the following IOI (Figure 9d), and the smallest effect when tapping is restarted at the pulse change (Figure 9a). The phase shift found in the last condition can perhaps still be explained by a heightened sensitivity of the period correction mechanism to the pulse change. The puzzling result is the total absence of a phase shift in the condition in which taps in Positions P − 1 and P were skipped (Figure 9c). This finding still defies explanation.

I should also mention that considerable individual differences were present in this experiment. The results are mainly representative of the four undergraduate participants. Three of the other participants, at least two of whom had greater musical experience than the undergraduates, did not show any substantial phase shifts.

I myself showed a phase shift in the Skip P condition but not in the Skip P − 1 condition, in which my slow phase correction process dominated.

Experiment 5

The original motivation of Experiment 5 (conceived while Experiment 4 was in progress) was to provide another test of the hypothesis that a subliminal timing perturbation can be registered perceptually and used for phase correction in tapping. The task required intermittent rather than interrupted tapping. There were only two conditions, which are illustrated schematically in Figure 11. In one condition, participants were required to make a single tap in Position P + 1 following a pitch cue. In the other condition, participants made two taps, in Positions P and P + 1. The question being investigated was whether phase correction would be evident in the first condition in which no sensorimotor asynchrony is available at the point of perturbation. The second condition served as a baseline for comparison. Given the results of Experiment 4, however, it was expected that complete phase resetting would occur in the first condition. Thus, the question of interest changed to whether overcorrection and a progressive phase shift would be evident as well, as in the Skip P condition of Experiment 4, and whether the results of the second condition would resemble the Skip P − 1 condition.

Method

Participants. There were 6 participants, including a new male volunteer (age 41) who had little musical training, myself, and the same 4 female undergraduates as in the preceding experiments (whose musical training ranged from little to moderate). Three of the earlier participants were no longer available; they were the ones who had not shown any phase shift in Experiment 4.

Stimuli. The sequences were the same as in Experiment 4 except for a change in the location of the lower-pitched cuing tones in each sequence. There were two sets of sequences. In the P set, the last tone in each triplet of lower-pitched tones occurred in Position P − 1, as in the P set of Experiment 4. In the new P + 1 set, the last lower-pitched tone occurred in Position P.

Procedure. The two conditions were presented in fixed order in a single session. In the first condition, using the P + 1 set of sequences, participants were required to make a single tap after each group of lower pitched tones such that the tap coincided with the next (high-pitched) tone. In the second condition, using the P set, participants made two taps following each group of lower-pitched tones such that the taps coincided

with the next two high-pitched tones. Otherwise, the design was the same as in the previous experiment.

Results and Discussion

The grand average asynchrony was −34 ms in both conditions, which was very similar to what had been observed in Experiment 4 after an interruption in tapping (see Figure 8), and there was no significant difference between the two positions in the two-tap condition. The raw asynchronies of each condition were entered into an ANOVA with the variables of episode (4), direction of perturbation (2), magnitude of perturbation (2), and, in the two-tap condition, position (2). The main effect of episode was nonsignificant in both conditions, although there was a small trend similar to that observed in Experiment 4, with asynchronies becoming more negative after the first episode. More important, episode did not significantly interact with either direction or magnitude in either condition. This means that there were no progressive phase shifts.

Figure 10f presents the results in terms of slopes of regression lines fitted to the asynchronies in the four Δt conditions. The condition of making taps in Positions P and P + 1 corresponds to the Skip P − 1 condition in Experiment 4 (Figure 10a) because, in each case, the first tap after the interruption coincided with the perturbed tone. The results were very similar indeed, showing rather rapid but not immediate phase correction. An ANOVA on the asynchronies yielded the expected significant main effects and interactions. A separate ANOVA on Position P + 1 still showed only a significant main effect of direction, $F(1, 5) = 8.4, p < .04$, and a Direction × Magnitude interaction, $F(1, 5) = 7.8, p < .04$, which confirmed that phase correction was not yet complete.

The condition in which a single tap was made in Position P + 1 corresponds to the Skip P (Figure 10b) and Skip P − 1 and P (Figure 10c) conditions of Experiment 4. Surprisingly, the results matched those of the former condition, not of the latter. In other words, there was overcompensation shown by all 6 participants. An ANOVA showed a significant main effect of direction, $F(1, 5) = 21.8, p < .006$, and a Direction × Magnitude interaction, $F(1, 5) = 23.9, p < .005$. However, this phase shift in response to a perturbation was not carried forward to the next single tap in the same trial and thus was not cumulative.

These results are consistent with the phase resetting plus period correction explanation proposed in connection with Experiment 4. The tap made in Position P + 1 must obviously be timed from the preceding tone, because there are no preceding taps. This results in phase (re)setting. The interval between the tone and the tap is governed by the timekeeper period, which is essentially a running estimate of the sequence period (with adjustment for perceptual and motor delays; see Mates, 1994a), and that period is evidently influenced by the most recent IOI, absorbing about 40% of Δt. It is important to note that the timing of the tap could not simply be governed by an attentional oscillator that adapts its phase, period, or both in response to the perturbation (Large & Jones, 1999), for in that case undercorrection should be evident, just as in Position P + 1 of the two-tap condition. It is necessary to assume that phase resetting occurred in addition to a partial period correction. Moreover, Large and Jones (1999) assumed period correction in the attentional oscillator to be very slow—too slow to account for the 40% overcorrection observed. These observations suggest that the
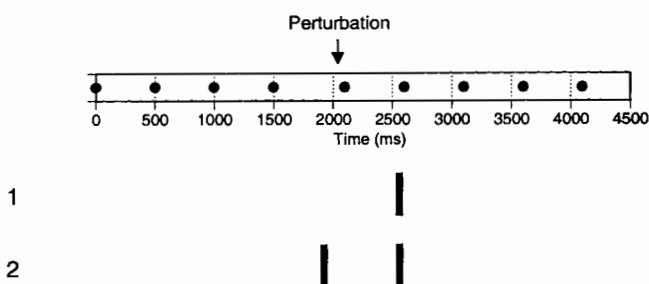

Perturbation

Figure 11. Schematic diagram of the two tapping conditions in Experiment 5. The size of the perturbation is exaggerated for visual effect.

phase and period of tapping are governed by a separate motor timekeeper whose flexibility is increased by the discontinuity in the motor activity.

General Discussion

The present series of experiments extends earlier research (Repp, 2000a) demonstrating that subliminal pulse changes are rapidly compensated for in sensorimotor synchronization. The results lend further support to the conclusion that psychophysical detection thresholds for differences in duration or temporal order, which are based on conscious decisions and explicit judgments (i.e., delayed, categorical, verbal acts; cf. Neumann, 1990b), are irrelevant to the temporal control of ongoing actions. Such actions seem to be coordinated with environmental events by means of a process of direct parameter specification (Neumann, 1990a) or perception–action coupling (Kelso & Kay, 1987) or entrainment (Jones, 1976; Thaut, Miller, et al., 1998) that is sensitive to timing differences well below the level of awareness. Presumably, that process of coordination and error correction involves lower-level, phylogenetically old brain structures, with the cerebellum being a prime candidate (see, e.g., Harrington, Haaland, & Knight, 1998; Ivry, 1997; Ivry & Keele, 1989; Parsons & Fox, 1997; Rao et al., 1997).

Experiment 1 addressed some doubts that had remained about whether the compensation for subliminal pulse changes reflected phase correction, period correction, or both. Using continuation tapping as a probe into the state of the timekeeper period immediately following a subliminal perturbation, Experiment 1 yielded results that suggested that a single changed IOI in the stimulus sequence does not result in any significant period correction when tapping is continuous. This supports the assumption made in two-tiered models of error correction (Mates, 1994a, 1994b; Pressing, 1998; Semjen et al., 1998; Vorberg & Wing, 1996) that stimulus phase shifts result in local phase corrections that leave the underlying period unaffected. The results of Experiment 1 suggest that at least two or three successive IOIs must be changed to have an effect on the timekeeper period and that more than five consecutive changed IOIs are needed for complete period correction to occur. This topic is pursued further in Repp (in press).

Before discussing the results of Experiments 2–5, it may be useful to contemplate that there are at least three levels of temporal information: time points, intervals (i.e., differences between time points), and differences between intervals. The two-tiered error correction model of Mates (1994a, 1994b; see Appendix A) takes an interval, the sensorimotor asynchrony, to be the informational basis of phase correction and a difference between intervals, namely between the sequence IOI and the timekeeper period, to be the basis of period correction. By contrast, Hary and Moore (1985, 1987) proposed a model in which time points are the basis of phase correction, whereas an interval, the asynchrony, is the basis of period correction. They argued that phase correction results from a random mixture of two phase resetting processes, one stimulus based and the other response based. Stimulus-based phase resetting amounts to perfect phase correction ($\alpha = 1$ in Equation A1 of Appendix A), whereas response-based phase resetting amounts to no phase correction ($\alpha = 0$). Schulze (1992) subsequently showed that this model is formally equivalent to the linear phase correction model ($0 < \alpha < 1$), which has been favored by recent authors.

Indeed, there is something unappealing about the notion of randomly alternating discrete processes. However, is it not just as unsatisfactory to assume that merely a certain percentage of every perturbation is compensated for? What prevents perfect compensation from occurring?

One possible answer to this question is that there are two competing processes in synchronized tapping. One process, sensorimotor coupling, tries to adapt to changes in the stimulus sequence and is equivalent to continuous stimulus-based phase resetting. The other process, motor persistence, tries to maintain a regular periodic activity and is equivalent to continuous response-based resetting. Rather than alternating randomly, sensorimotor coupling and motor persistence may be in a continuous dynamic balance that can be tilted one way or another by various task factors. Factors that weaken sensorimotor coupling tilt the balance in favor of motor persistence. Factors that weaken motor persistence tilt the balance in favor of sensorimotor coupling.

Experiments 2–5 investigated whether phase correction occurs when there is no tap coinciding with a subliminally perturbed tone. The evidence was clearly positive; thus, there are other ways of registering a perturbation than by means of a sensorimotor asynchrony. However, Experiments 2–3 and Experiments 4–5 differed in the proposed dynamic balance between sensorimotor coupling and motor persistence. First, in Experiments 2–3, the motor activity was continuous, whereas in Experiments 4–5, it was discontinuous. This discontinuity reduced the resistance of the motor control system to sensorimotor coupling and enabled stimulus-based phase resetting to occur. Second, according to instructions, the taps were usually not intended to be in phase with the tone sequence in Experiments 2–3, whereas they were always intended to be in phase in Experiments 4–5. Antiphase and arbitrary-phase relationships are likely to weaken sensorimotor coupling. There was some evidence that phase correction was impaired in the arbitrary-phase conditions of Experiment 3 but not in the antiphase condition of Experiment 2. Generally, phase correction was surprisingly effective in all these conditions. This was most likely due to a third important factor: The taps in Experiments 2–3 produced tones that could be perceptually integrated with the sequence tones to yield a rhythmic pattern. The taps thus became subservient to the perceptual strategy of maintaining an auditory rhythm (Semjen & Ivry, 2001), which strengthened the sensorimotor coupling. In Experiments 4–5, the taps did not produce tones and thus were governed by a more independent motor control process whose tight coupling to the auditory sequence was due to the inphase relationship between taps and tones.

The process by which phase correction was implemented in the antiphase and arbitrary-phase conditions of Experiments 2–3 remains a subject of speculation. The results are consistent with the operation of an attentional oscillator (Jones, 1976; Jones & Boltz, 1989; Jones & Yee, 1997; Large & Jones, 1999) that monitored the tone sequence, registered subliminal deviations from temporal expectations, and forwarded these asynchronies to the motor control system. This would not have occurred if the taps had not produced tones; in that case, stable antiphase or arbitrary-phase tapping would have been difficult or impossible. The attentional oscillator model proposed by Large and Jones (1999) clearly allows for the registration of subliminal timing perturbations, but it has been applied so far only to tasks requiring explicit temporal judgments in which subliminal perturbations would not have mea-

surable consequences. The present results, however, suggest that subliminal perturbations can indeed be registered perceptually and utilized in the temporal control of actions, but of course below the level of awareness. Because temporal expectation can be conceived as readiness for (some unspecified) action, it is possible that the so-called attentional oscillator is itself a covert action system and thus closely related to motor control.

In a recent study, Aschersleben and Müsseler (1999) found evidence that the asynchronies in synchronized finger tapping with a moving visual stimulus were subject to a movement-based illusion (the Fröhlich effect) that affects conscious judgments, whereas simple or choice reaction times were immune to this illusion. These authors concluded that synchronization requires more extensive stimulus processing than do simple motor actions. This conclusion is not necessarily in conflict with the present findings and with the concept of direct parameter specification. There may well be different degrees of directness that depend on the relative complexity of the processes underlying a task. The main criterion for directness is taken to be the absence of conscious perceptual mediation between sensory information and action. Contrary to what Aschersleben and Müsseler (1999, p. 1715) seem to be saying, participants in a synchronization task do not have to make a temporal order judgment or decision following each tap in order to achieve phase correction; rather, relative phase information is normally processed without awareness and thus informs action directly.

Some of the present findings require further investigation to be better understood. For example, it seems that the interruption of the motor activity in Experiments 4–5 enabled not only perfect phase correction (i.e., stimulus-based phase resetting) but also period correction to some extent, in contrast to Experiment 1 in which the motor activity was continuous. This period correction added to the phase resetting sometimes resulted in overcorrection that persisted and accumulated over several successive perturbations provided that tapping was only occasionally interrupted (Experiment 4). When tapping was truly intermittent (Experiment 5), the overcorrection was not cumulative. Moreover, it did not occur in some tapping conditions of Experiment 4 and the reasons for this need to be clarified in future research. Synchronized finger tapping, a deceptively simple task, harbors quite a few complexities when examined closely.

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Appendix A

The Behavioral Ambiguity of Phase Versus Period Correction

The linear two-process error-correction model in Mates (1994a) includes several sources of additive variability that are assumed to be normally distributed with a mean of zero. If data are averaged over a number of trials as in the present research, the predictions of the model can be formulated in terms of expected values of internal variables. In this simplified version, the expression for phase correction is

$$a(k + 1) = (1 - \alpha)a(k) + t(k) - c(k), \tag{A1}$$

where $a(k)$ is the perceptually registered asynchrony between the kth tap and the kth tone, $t(k)$ is the expected internal timekeeper period immediately preceding the kth tap, $c(k)$ is the perceptually registered interval between the $(k - 1)$th and kth tones in the sequence, and α is a phase correction parameter $(0 \leq \alpha \leq 1)$. In other words, the interval $t(k)$ generated by the timekeeper is adjusted by a proportion of the last asynchrony. The expression for period correction is

$$t(k + 1) = (1 - \beta)t(k) + \beta c(k), \tag{A2}$$

where β is a period correction parameter $(0 \leq \beta \leq 1)$. That is, the period is adjusted by a proportion of the difference between $t(k)$ and $c(k)$.

If a pulse change (phase shift) is introduced at event n in an otherwise regular sequence then $c(n - 1) = c + \Delta t$, with $c(k) = c$ for all other intervals $(k \neq n - 1)$. Assuming that $a(n - 1) = 0$ and $t(n - 1) = c$ (i.e., the asymptotic state aimed for by the human participant), it follows from Equation A1 that $a(n) = -\Delta t$. According to the model, this change to the internal asynchrony causes both a period correction (from Equation A2),

$$t(n) = (1 - \beta)t(n - 1) + \beta c(n - 1)$$

$$= (1 - \beta)c + \beta(c + \Delta t)$$

$$= c + \beta \Delta t, \tag{A3}$$

and a subsequent phase correction (from Equations A1 and A3),

$$a(n + 1) = (1 - \alpha)a(n) + t(n) - c(n)$$

$$= -(1 - \alpha)\Delta t + c + \beta \Delta t - c$$

$$= -\Delta t[1 - (\alpha + \beta)]. \tag{A4}$$

Thus, the first asynchrony following a phase shift depends only on the sum of the two error correction parameters. This is not true for subsequent asynchronies, but α and β do remain interchangeable. The general expression for the progressive adaptation of the timekeeper period following a perturbation is

$$t(n + j) = c + \beta(1 - \beta)^j \Delta t \qquad j = 0, 1, 2, \ldots, \tag{A5}$$

and the cumulative result of period correction and phase correction for the jth tap following a perturbation is

$$a(n + j) = -\Delta t[\beta(1 - \beta)^j - \alpha(1 - \alpha)^j]/(\beta - \alpha)$$

$$j = 0, 1, 2, \ldots. \tag{A6}$$

It is evident that the last equation is symmetric with regard to α and β.

It follows that in the context of this linear model, the internal consequences of phase correction and period correction cannot be distinguished. This holds also for the internal response to other kinds of perturbation, as I have shown by a simple computer simulation. The expected values of the observable asynchronies are assumed to differ from their internal representations only by an additive constant (typically negative), which is attributed in Mates's (1994a) model to different feedback delays for taps and sequence events. Therefore, to the extent that the linear two-process model holds, the behavioral consequences of internal phase correction and internal period correction are indistinguishable.[A1]

[A1] This appendix was prepared with the help of Dirk Vorberg, who derived the expressions stated in Equations A5 and A6.

Appendix B

Contextual Effects on The Timing of the Initial Tap in Experiment 1

At first glance, it seems paradoxical that the initial rate of the taps to slow sequences was too slow and the rate of the taps to fast sequences was too fast. The opposite would seem intuitively more plausible. However, what needs to be considered is the timing of the first tap (i.e., the interval between the first sequence tone and the first tap). That tap occurred in response to the first tone and in anticipation of the second tone, but it occurred too early in slow sequences and too late in fast sequences. To compensate for this initial error, the subsequent ITIs had to be lengthened in slow sequences and shortened in fast sequences, hence the paradoxical initial tempo of the taps.

Two factors may have influenced the timing of the initial tap: Participants may have adopted the strategy of starting each sequence at the same intermediate tempo, and/or they may have started at the tempo of the immediately preceding sequence. To investigate this issue, the times of occurrence of the initial taps, measured from sequence onset, were analyzed. The initial trial in each block was excluded. The remaining 200 trials were cross-classified according to the baseline tempi of the preceding sequence and the current sequence; the various perturbation conditions were combined. The average initial tap times for the resulting nine groups and the number of trials in each group are shown in Table B1.

Successive trials with the same baseline tempo were relatively infrequent because of an intentional bias in the randomization of trials. The standard deviation of participants' grand average initial ITIs was 28 ms, which indicates considerable individual differences in the mean interval duration. Nevertheless, the grand mean duration (522 ms) was significantly below the average IOI duration in the experiment (550 ms), $t(7) = 2.9, p <$

.01. In other words, participants generally started at a faster than average tempo. This may have been due to the fact that all had participated in many earlier experiments in which only a baseline IOI of 500 ms had been used. This tempo may have become a preferred tempo through practice.

A 3 × 3 repeated measures ANOVA on the data, with the variables of preceding tempo and current tempo, showed a significant main effect of preceding tempo, $F(2, 14) = 14.2, p < .0001$. However, the absolute magnitude of that effect (about 40 ms) was much smaller than the range of preceding tempi (100 ms), which indicates that participants did not simply continue at the preceding sequence tempo. Thus, the timing of the first tap seemed to be influenced both by preceding context and by a preferred starting tempo (which happened to be faster than the average tempo in the experiment).

Interestingly, the ANOVA also showed a significant main effect of current tempo, $F(2, 14) = 5.9, p < .02$, and a significant two-way interaction, $F(2, 14) = 5.1, p < .003$. How could the current tempo, which was defined by the first sequence IOI, have had an influence on the timing of the first tap? As can be seen in Table B1, the current tempo exerted an effect only when the preceding tempo was slow. In that case, the first tap occurred relatively late. Because there was considerable variability, the first tap often occurred well after the second sequence tone, especially when the first IOI was short. Thus, the first IOI could have had an influence on the execution of the first tap while the finger movement was already in progress. What is puzzling is the direction of the effect: The first tap made when the first IOI was short occurred later than the first tap made when the first IOI was long. Rather than attracting the first tap, the arrival of the second sequence tone before the tap apparently delayed the tap slightly. This finding awaits explanation.

The adjustment of the initial ITIs to the current sequence tempo must have required period correction as well as phase correction. Period correction may have been more rapid at the beginning of a sequence than later in the sequence in response to subliminal changes in IOI duration, because the difference between the initial IOI and the initial timekeeper period probably often exceeded the detection threshold (Repp, in press). It is also possible that a mixture of different strategies was used in this initial "tuning in" (see Semjen et al., 1998).

Table B1
Average Times of Occurrence (in Milliseconds) of Initial Taps in Experiment 1 and Number of Trials (n) in Each Group

Current IOI (ms)	Preceding baseline IOI		
	500 ms	550 ms	600 ms
500	501 ($n = 10$)	529 ($n = 26$)	549 ($n = 34$)
550	499 ($n = 32$)	523 ($n = 8$)	540 ($n = 26$)
600	504 ($n = 24$)	523 ($n = 32$)	533 ($n = 8$)

Note. IOI = interonset interval.