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Processes underlying adaptation to tempo changes in sensorimotor synchronization

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Abstract

In synchronizing finger taps with an auditory sequence, a small sudden tempo (“step”) change in the sequence tends to be followed by rapid adaptation of the tapping period but slow adaptation of the relative phase of the taps, whereas a larger step change leads to initial period overshoot followed by rapid adaptation of both period and phase [M.H. Thaut, R.A. Miller, L.M. Schauer, *Biological Cybernetics* 79 (1998a) 241–250]. Experiment 1 replicated these findings and showed that the transition between the two patterns of adaptation occurs near the perceptual detection threshold for a tempo change. A reasonable explanation of these data was provided by a dual-process model of internal error correction [J. Mates, *Biological Cybernetics* 70 (1994a) 463–473, 70 (1994b) 475–484], with the added assumption that one process (period correction) depends on conscious awareness of a tempo change whereas the other (phase correction) does not. This assumption received support in Experiment 2, where a synchronization-continuation tapping task was used in combination with perceptual judgments to probe into the process of period correction following step changes. The results led to the conclusion that rapid adaptation of the tapping period to a small, undetected tempo change is in fact due to rapid internal phase correction, whereas slow adaptation of the relative phase of the taps is due to slow internal period correction. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

1.1. *Two error correction processes*

When a task requires the coordination of a repetitive action, such as finger tapping, with a periodic stimulus, such as a sequence of tones, some form of error correction is required to achieve and maintain synchronization. Without such correction, error variance due to internal timekeeper variability (Wing & Kristofferson, 1973) would accumulate and inevitably lead to lack of synchrony, even when the period of the motor activity equals that of the stimulus sequence (Hary & Moore, 1987a; Vorberg & Wing, 1996). Two internal error correction processes have been distinguished: phase correction and period correction (Mates, 1994a,b; Repp, 2000, 2001; Semjen, Vorberg, & Schulze, 1998; Vorberg & Wing, 1996).¹

Within the theoretical framework adopted here, phase correction is considered to be a local adjustment to the interval generated by an internal timekeeper; it leaves the period of the timekeeper unaffected. The informational variable on which phase correction is based is the internal asynchrony (also called synchronization error or phase error), which is a function of the observable asynchrony between tone and tap. Phase correction is believed to be sufficient for maintaining synchronization with an isochronous stimulus sequence (Pressing, 1998; Semjen et al., 1998; Semjen, Schulze, & Vorberg, 2000; Vorberg & Wing, 1996). Period correction appears to come into play only when the period of the stimulus sequence is changed in a systematic way (Repp, 2001, in press-a). Period correction modifies the period (also called the reference interval) of the timekeeper that paces the motor activity. The informational variable on which period correction is based is assumed to be the difference between the current timekeeper period and the internally rep-

¹ As is evident from this introductory paragraph, the present study was conducted within the theoretical frameworks of cognitive psychology and linear statistical modeling. A dynamic systems approach would use nonlinear equations and do away with internal processes, but it may nevertheless turn out to be similar in important respects (see Large & Jones, 1999; Pressing, 1999). At present, I am not sufficiently versed in dynamic theory to wield its tools with confidence.

resented duration of the most recent inter-onset interval (IOI) in the tone sequence.

From this perspective, it is important to distinguish between external (observable) and internal (inferred) variables or processes (Mates, 1994a). The terms “period (correction)” and “phase (correction)” have been applied to both, which can cause confusion. The internal timekeeper period, which is not directly measurable, must be distinguished from the observable inter-tap intervals (ITIs), which are sometimes referred to as the tapping period. Likewise, the internally represented phase relationship between tone and tap is not necessarily identical with the measurable asynchrony or relative phase. Error correction processes, which are necessarily internal, operate on internal variables and produce observable consequences. It is important to realize that period correction and phase correction affect both the observable period (ITIs) and the observable phase (asynchronies) of the finger taps, so that each of these hypothetical internal processes can give rise to exactly the same overt synchronization behavior, at least within the simple linear model proposed by Mates (Repp, 2001). To observe the internal–external distinction, the terms “period” and “phase” will be used henceforth to refer to internal variables only, whereas the observable variables will be called “ITIs” and “asynchronies”. Furthermore, internal processes will be referred to as “correction”, whereas their observable consequences will be called “adaptation”.

The distinction between internal and external variables is supported by the commonly observed anticipation tendency in synchronization (i.e., taps tend to precede tones), which suggests that the internal representation of asynchronies is not veridical (see, e.g., Aschersleben & Prinz, 1995; Semjen et al., 1998). The anticipation tendency can be reduced by sensory feedback manipulations (Aschersleben & Prinz, 1997; Fraisse, Oléron, & Paillard, 1958) or by filling sequence IOIs with other sounds, which affects time perception (Wohlschläger & Koch, 2000).

An internal process that may play a role in sensorimotor synchronization is conscious awareness of temporal change, either in IOIs or in asynchronies. Error correction in synchronization has been shown to occur in response to subliminal perturbations of sequence timing (Hary & Moore, 1985, 1987a; Repp, 2000, 2001; Thaut, Miller, & Schauer, 1998a; Thaut, Tian, & Azimi-Sadjadi, 1998b). This suggests that the internal processes that control the timing of the synchronized action are directly coupled to the sensory information, without any mediation by awareness or perceptual judgment. However, this can be said confidently only with regard to phase correction

(Repp, 2000, 2001). The main purpose of the present research was to investigate to what extent period correction may depend on conscious awareness of a tempo change.

1.2. Studies of adaptation to tempo changes

To engage the period correction process (in addition to phase correction) in synchronization, a tempo change in the pacing sequence is required. Pioneering research was conducted by Michon (1967) who introduced “step changes”, that is abrupt changes in sequence tempo (IOI duration), with the sequence being stationary (isochronous) before and after the change. The changes were fairly large (8% or more of the baseline IOI), and synchronization with the new tempo was generally achieved within 4–5 taps. Plots of ITIs showed an initial overshoot, followed by a gradual approximation of the new IOI duration. Michon did not distinguish between phase and period correction. Instead, he formulated an ideal linear predictor model according to which the current ITI is derived from the two preceding IOIs: $ITI(k) = 2 \times IOI(k - 1) - IOI(k - 2)$ (see also Michon & van der Valk, 1967). Note that this model includes observable variables only. It accounts for the initial overshoot, but it also predicts that subsequent adaptation to the new tempo should be immediate. Since this was not the case, an additional parameter had to be introduced to account for the gradual time course of the adaptation (which, incidentally, showed considerable individual differences).

Hary and Moore (1985, 1987a) introduced step changes of much smaller size – 1.3% (10 ms) of the baseline IOI (700 ms) – which were not detectable by ear. In analyzing the data they relied mainly on computer modeling of the auto- and cross-correlations of the IOIs and ITIs, assuming internal phase and period correction processes governed by model parameters. On the basis of this modeling, they proposed that period correction occurred only very gradually in combination with a mixed resetting (i.e., phase correction) strategy. According to that strategy, the interval preceding the next tap (the “internal delay”) is sometimes measured from the previous tap (no phase correction) and sometimes from the previous tone (perfect phase correction). Schulze (1992) subsequently demonstrated that a mixed phase resetting model is formally equivalent to a phase correction model in which the current timekeeper interval is always adjusted by a certain proportion of the most recent asynchrony. This is the linear phase correction model espoused subsequently by Mates (1994a), Pressing (1998), Vorberg and Wing (1996),

Semjen et al. (1998, 2000), and Repp (2000, 2001), among others. Pressing (1998) and Semjen et al. (1998) extended the model to take the penultimate synchronization error into account, but such second-order phase correction seems to play a role only at very fast tempi or with expert tappers. Most of these recent synchronization studies have been concerned with phase correction only.

Mates (1994a,b) proposed the model that forms the theoretical background for the present study. It includes linear phase correction and period correction processes. Phase correction is a proportion α of the most recent (internally represented) asynchrony, whereas period correction is a proportion β of the (internally represented) difference between the most recent IOI and the time-keeper period. Mates showed that his model can explain the initial ITI overshoot in response to a large step change (Michon, 1967) as the result of simultaneous imperfect phase correction ($\alpha < 1$) and perfect period correction ($\beta = 1$), but he did not seem to realize that the same result can be achieved by interchanging the values of α and β (see Repp, 2001). Thus, while the overshoot suggests the simultaneous operation of both error correction processes, it is not clear which process is the more efficient one. Mates also pointed out that the model parameters arrived at by Hary and Moore (1985, 1987a) cannot account for the ITI overshoot, but he did not take into account that these parameters applied to data obtained with very small step changes. Hary and Moore argued that adaptation to these small changes involves very slow period correction but more rapid phase correction, contrary to what Mates assumed to be the case for the larger step changes studied by Michon (1967). It is possible that different error correction strategies are used in the two cases.

This suggestion received support in a recent study by Thaut et al. (1998a) which employed both small (presumably subliminal) and larger (presumably supraliminal) step changes, though their detectability was not assessed directly. The steps were of three magnitudes: 10, 20, and 50 ms, with a baseline IOI of 500 ms. The results for the 50-ms steps resembled those of Michon (1967) in that they showed fairly rapid adaptation of ITIs, following an initial overshoot. The results for 10-ms and 20-ms steps likewise showed rapid adaptation of ITIs, but without initial overshoot. Adaptation was somewhat faster to positive step changes (decelerations) than to negative step changes (accelerations). Thaut et al. also examined the asynchronies and found that they adapted rapidly (i.e., returned to the average value of the asynchronies before the step change) after the 50-ms step change but – and this is their major new result – only very slowly after the smaller step changes. Although Thaut et al. were aware of Mates's (1994a,b) model, they preferred to apply a multiple linear regression model

which eschewed internal processes and thus was based solely on observable variables (IOIs, ITIs, and asynchronies). They concluded that period correction takes priority over phase correction after small step changes (contrary to Hary & Moore, 1985, 1987a) but that phase correction comes to the fore after larger step changes, once a tolerance threshold for synchronization errors is exceeded (contrary to Repp, 2000, who found that phase correction is not limited by a threshold). These apparent contradictions result from the fact that Thaut et al. were using the terms “period correction” and “phase correction” to refer to observable behavior (viz., adaptation of ITIs and asynchronies, respectively) whereas Hary and Moore and I were using the same terms to denote internal processes underlying the behavior.²

1.3. The present study

Two experiments are reported here. The purpose of Experiment 1 was to replicate the findings of Thaut et al. (1998a) and to interpret them from the perspective of the two-process model of error correction (Mates, 1994a). The main hypothesis was that the different patterns of adaptation following small and large step changes reflect a role of conscious awareness of a tempo change. Psychophysical data suggest a detection threshold of about 2% for step changes relative to a baseline IOI of 500 ms (Drake & Botte, 1993; Friberg & Sundberg, 1995; McAuley & Kidd, 1998; Michon, 1967). Thus, a 10-ms step (2%) should be detectable some of the time, whereas 20-ms (4%) and 50-ms (10%) steps should be detectable most of the time. However, Thaut et al. found that 10-ms and 20-ms steps gave rise to similar patterns of results. This seems to argue against the hypothesis that awareness of a tempo change plays a role, but their participants (untrained undergraduate students) may well have had higher detection thresholds than the trained listeners in the studies cited above. In the present Experiment 1, step sizes ranging from 1% to 5% were used, and the participants were more experienced than those of Thaut et al. In addition to tapping in synchrony with the sequences, they were required to report and identify any tempo changes they had heard. It was predicted that the transition from one adaptation pattern to the other (if replicated) would coincide approximately with the average detection threshold, defined as 50% correct responses. In this combined synchroniza-

² It took me some time to understand this difference. Volman and Geuze (2000, p. 66) also may have misunderstood the conclusions of Thaut et al.

tion and detection task, it was also possible to compare trials on which a step change was detected to trials on which the same step change was not detected. A finding of different response patterns in this comparison would further support the hypothesis that explicit detection of a tempo change causes the change in adaptation patterns. Experiment 1 also included an attempt to show that the results are at least qualitatively consistent with the linear two-process error correction model of Mates (1994a).

Experiment 2 went one step further by adding a continuation tapping task to the synchronization-and-detection task of Experiment 1. The specific hypothesis addressed here was that awareness of a tempo change facilitates period correction. It was pointed out earlier that period correction and phase correction are interchangeable within the two-process model; therefore, the process affected by awareness (if any) could not be pinpointed in Experiment 1. The purpose of the continuation tapping task was to resolve this ambiguity. The ITIs of continuation tapping were assumed to reflect the period of the internal timekeeper at the end of the preceding sequence, so that the time course of the internal period correction process could be gauged by switching from synchronization to continuation at various distances after a step change (see also Repp, 2001: Exp. 1). This analysis was made contingent on whether the step change was or was not detected. It was predicted that period correction would be slow for undetected step changes but faster for detected step changes, regardless of step magnitude.

2. Experiment 1

2.1. *Methods*

Participants. All eight participants were fairly practiced in synchronized tapping, having served in a number of previous experiments. They included the author (male, age 54), a research assistant (male, age 38), and six paid volunteers (three males around the age of 30, and three female undergraduates around the age of 19). Four of the male participants had extensive musical training (10 years or more), which was expected to reduce timing variability and increase sensitivity to tempo changes; the others had more limited musical experience.

Materials. The stimulus sequences were produced on a Roland RD-250s digital piano under control of a MAX patch running on a Macintosh Quadra 660 AV computer, which was connected to the piano via a musical

instrument digital interface (MIDI) translator.³ Each stimulus sequence consisted of 25 high-pitched digital piano tones of constant frequency (C_8 , MIDI pitch 108, fundamental frequency 4168 Hz) and a nominal duration of 20 ms. The tones (sounding rather like pings) had sharp onsets and decayed rapidly over time. The baseline IOI duration was 500 ms. Each sequence contained a single step change in one of 10 possible positions, ranging from the 7th to the 16th tone in the sequence. From that tone onwards, all IOIs were longer or shorter than the baseline IOI by a fixed amount Δt . The absolute magnitude of Δt ranged from 5 to 25 ms in 5-ms increments. Thus there were 100 different sequences altogether (2 step directions \times 5 step magnitudes \times 10 step positions), which were arranged into five blocks of 20 trials each. The order of sequences within blocks was random. The five blocks were presented twice, so that each participant received each of the 10 step changes 20 times.

Procedure. Participants sat in front of a computer monitor which displayed the current trial number. They listened to the sequences over Sennheiser HD540 II earphones and tapped on a Fatar Studio 37 MIDI controller (a silent three-octave piano keyboard) by depressing a white key with the index finger of the preferred hand in synchrony with the sequence tones. The controller was held on the lap, the finger remained in contact with the key at all times, and it was suggested that the unsupported tapping arm be moved from the elbow to avoid fatigue. (However, there were individual differences in preferred tapping style.) The response key had a cushioned bottom contact and did not produce any audible sound. A key depression was registered about halfway during the downward trajectory. Participants were instructed to start tapping with the second tone in each sequence. After a sequence had ended, they were required to press one of three keys on the computer keyboard: the left-arrow key if a deceleration of tempo had been detected, the right-arrow key if an acceleration had been detected, or the down-arrow key if no change in tempo had been detected. Participants were informed that all sequences contained a tempo change, but they were asked to report a change only when they had really heard it. Depression of one of the computer keys started the next sequence after a delay of 4 s.

³ A MAX patch is a program written in the graphical programming language MAX. Due to a peculiarity of this software, the tempo of the output was about 2.4% faster than specified in the MIDI instructions. The participants' key presses were registered at a correspondingly slower rate. Throughout this paper, all stimulus specifications and results are reported as they appeared in the MAX environment. Apart from the constant scaling factor, MAX was highly accurate (within 1 ms) in timing the sequences and registering the key presses.

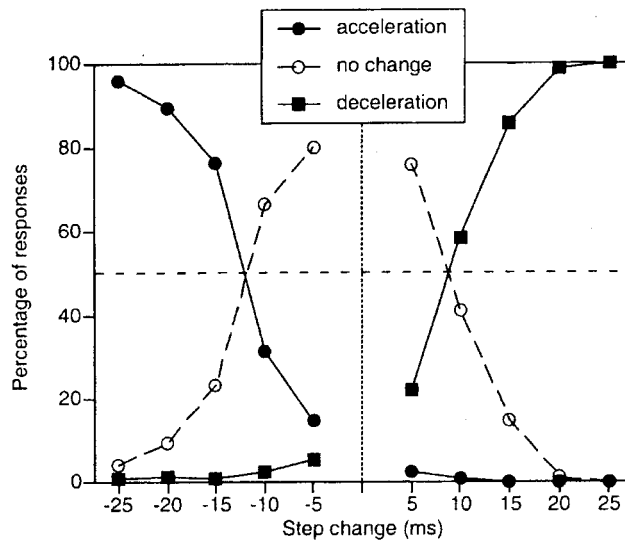


Fig. 1. Average percentages of detection responses as a function of step change magnitude (Exp. 1).

2.2. Results and discussion

Detection responses. Fig. 1 presents the results of the detection task. The average percentages of the three types of response (acceleration, deceleration, or no change) are shown as a function of Δt . As expected, positive detection responses increased monotonically with the absolute magnitude of Δt . The direction of a tempo change was rarely misidentified. However, there was an asymmetry in that decelerations ($+\Delta t$) were somewhat easier to detect than accelerations ($-\Delta t$). This difference was significant in a one-way repeated-measures ANOVA on the response percentages, $F(1, 7) = 19.7$, $p < 0.003$. This asymmetry is in accord with previous findings on tempo discrimination by musicians (e.g., Kuhn, 1974; Madsen, 1979). The average detection thresholds, defined here as the 50% cross-over points of the correct response functions, were near 2%, as expected: about -12 ms (2.4%) for accelerations and $+9$ ms (1.8%) for decelerations. One participant (surprisingly, one of the musically less experienced undergraduates) had thresholds below ± 5 ms ($\pm 1\%$).⁴ The average thresholds are representative of the other seven participants.

⁴ In part, this participant's low thresholds were due to a very low rate of "no change" responses. Nevertheless, her correct identifications of the direction of 5-ms step changes were about three times as frequent as her incorrect identifications.

Inter-tap intervals. Fig. 2 shows the average ITI durations for negative and positive Δt values as a function of sequence (IOI) position, starting four IOIs before the step change (position 0). The dashed horizontal lines indicate the sequence IOI durations. The standard error bars represent between-participant variability. It is clear that the ITIs adapted to the new IOIs at all values

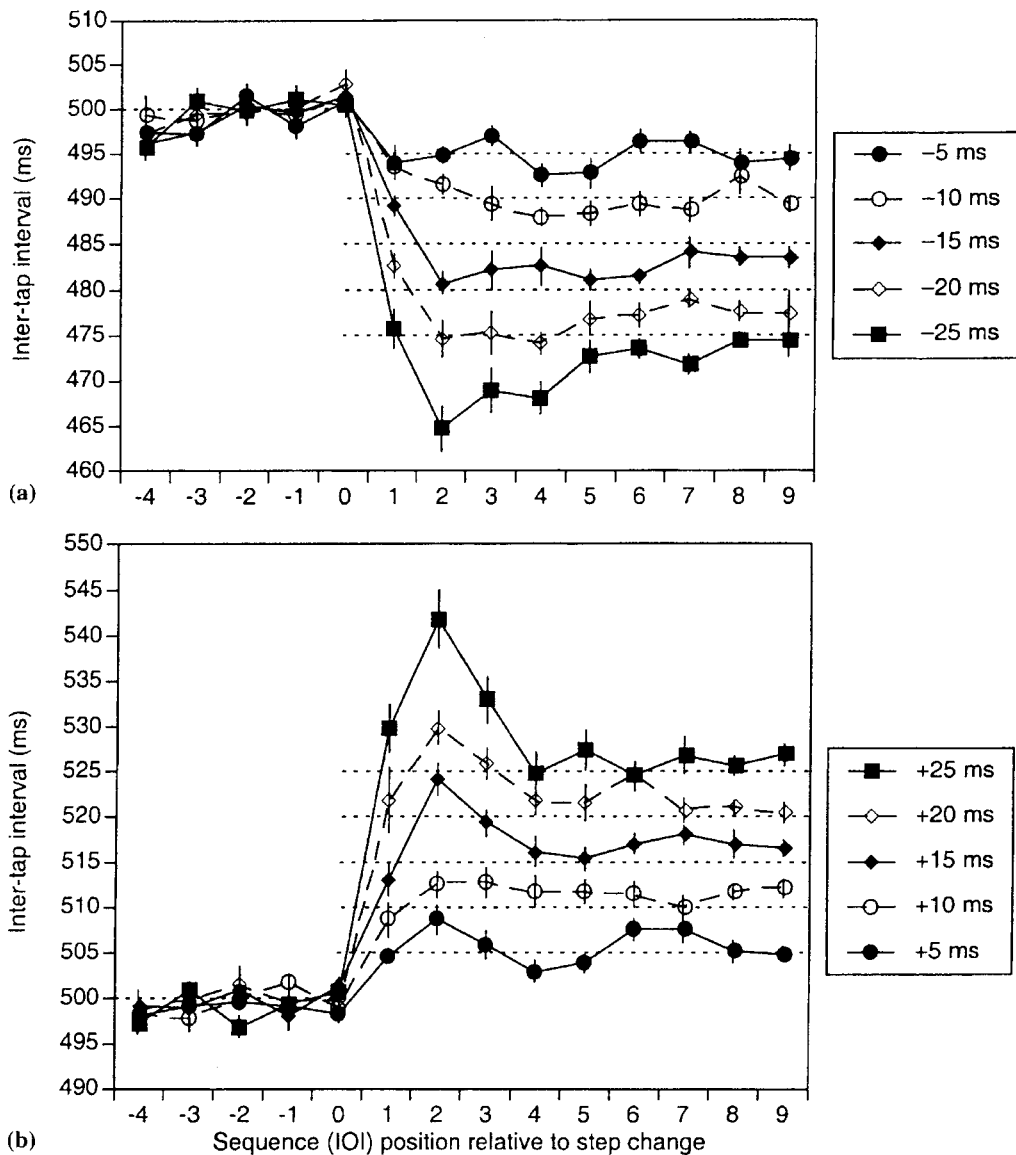


Fig. 2. Average inter-tap interval durations as a function of sequence position (step change = 0), for (a) negative steps and (b) positive steps, with standard error bars (Exp. 1).

of Δt . For Δt values of ± 5 and ± 10 ms, adaptation was rapid and showed no initial overshoot. At larger Δt values, initial overshoot was clearly evident, particularly in the second ITI following the step change. Consequently, adaptation of the ITIs to the new tempo was slower in these conditions, taking about four ITIs for positive Δt values and up to seven ITIs for negative Δt values. The overshoot was larger but subsided more rapidly for positive than for negative values of Δt . Although individual data were naturally more variable than the average data, the average pattern seemed reasonably representative of all participants.

A repeated-measure ANOVA was conducted on the ITIs in positions 1–6, with the fixed variables of direction (2), magnitude (5), and position (6).⁵ The data for negative Δt values were reflected around the 500-ms axis, in order to compare directly the time course of adaptation to positive and negative step changes. In addition to the trivially significant main effect of magnitude, the analysis revealed a significant main effect of position, $F(5, 35) = 6.5$, $p < 0.0002$, reflecting the decline of the initial overshoot over positions; a significant Magnitude \times Position interaction, $F(20, 140) = 3.5$, $p < 0.0001$, reflecting the fact that initial overshoot was obtained for larger but not for small Δt values; and a significant Direction \times Position interaction, $F(5, 35) = 4.3$, $p < 0.004$, reflecting the greater overshoot and more rapid decline obtained for positive than for negative Δt values. The triple interaction was not significant, $F(20, 140) = 1.2$, $p < 0.29$.

These results are quite similar to those of Thaut et al. (1998a), but they are compressed into a smaller range of Δt values: The Thaut et al. results for 10-ms and 20-ms steps resemble the present results for 5-ms and 10-ms steps (although ITI adaptation was more rapid here), and their ITI results for 50-ms steps resemble the present results for steps of 15–25 ms. A plausible explanation of this apparent rescaling is that the present listeners were perceptually more sensitive to the tempo changes in the sequences than the listeners of Thaut et al. This explanation assumes that the ITI overshoot is a consequence of explicit awareness of tempo changes. Indeed, in the present data the overshoot begins to emerge as the Δt values cross the detection threshold. The greater overshoot after positive than after negative step changes is also consistent with the greater detectability of positive step changes.

⁵ One reviewer has pointed out that the assumptions underlying univariate repeated-measures ANOVA may be violated by average time-series data. Therefore, the significance levels for effects involving position may not be accurate. Nevertheless, significant results do indicate that the pattern of results was consistent across participants. The interpretation of the data does not rest heavily on the statistical analysis.

To examine whether awareness of a tempo change plays a role in ITI adaptation, average ITIs were calculated contingent on whether or not a step change was detected, holding step size constant. This analysis was conducted mainly on the data for the $\Delta t = \pm 10$ ms trials, which could be divided into two groups for most participants, according to whether or not a correct tempo change had been reported.⁶ The average ITIs for the two types of trial (step change detected or not detected) are shown in Fig. 3 for negative and positive steps, respectively, with standard error bars representing between-participant variability. There was no clear indication of any incipient ITI overshoot contingent on explicit detection of a negative step (Fig. 3(a)). For positive steps, however (Fig. 3(b)), there was a difference in the expected direction in position 2. The difference was locally significant, as indicated by the non-overlapping standard error bars. A repeated-measures ANOVA on the positive Δt condition with the fixed variables of detection response (2) and position (6) showed the main effect of response to be significant, $F(1, 7) = 15.5$, $p < 0.006$ (although an unexpected difference in position 6 contributed to this effect), but the Response \times Position interaction only approached significance, $F(5, 35) = 2.4$, $p < 0.06$. On the whole, these results offer only weak support for the hypothesis that awareness of a tempo change causes ITI overshoot. It should be noted that the main hypothesis of this study was that internal period correction, not ITI adaptation, depends on awareness of a tempo change. Since ITI adaptation depends on both period and phase correction (see below), the results bear only indirectly on the main hypothesis.

Asynchronies. The asynchronies were generally negative (i.e., taps preceded tones), as is common in synchronization tasks (see, e.g., Aschersleben & Prinz, 1995). To eliminate individual differences in average asynchronies, which were of little interest here and would have inflated between-participant variability, the raw asynchronies were converted into relative asynchronies by subtracting the average of the five asynchronies preceding a step change from all asynchronies in that trial, thereby setting the average pre-step baseline to zero in all Δt conditions. These relative asynchronies are shown as a function of sequence position in Fig. 4. At the point of the step change (position 0, which denotes here the first shifted tone onset), the average asynchronies

⁶ For one participant, the data for $\Delta t = \pm 5$ ms had to be substituted, and for another participant, it was the data for $\Delta t = +15$ ms. In the statistical analysis, these ITIs were rescaled to $\Delta t = \pm 10$ ms (i.e., they were multiplied by 2 and 2/3, respectively).

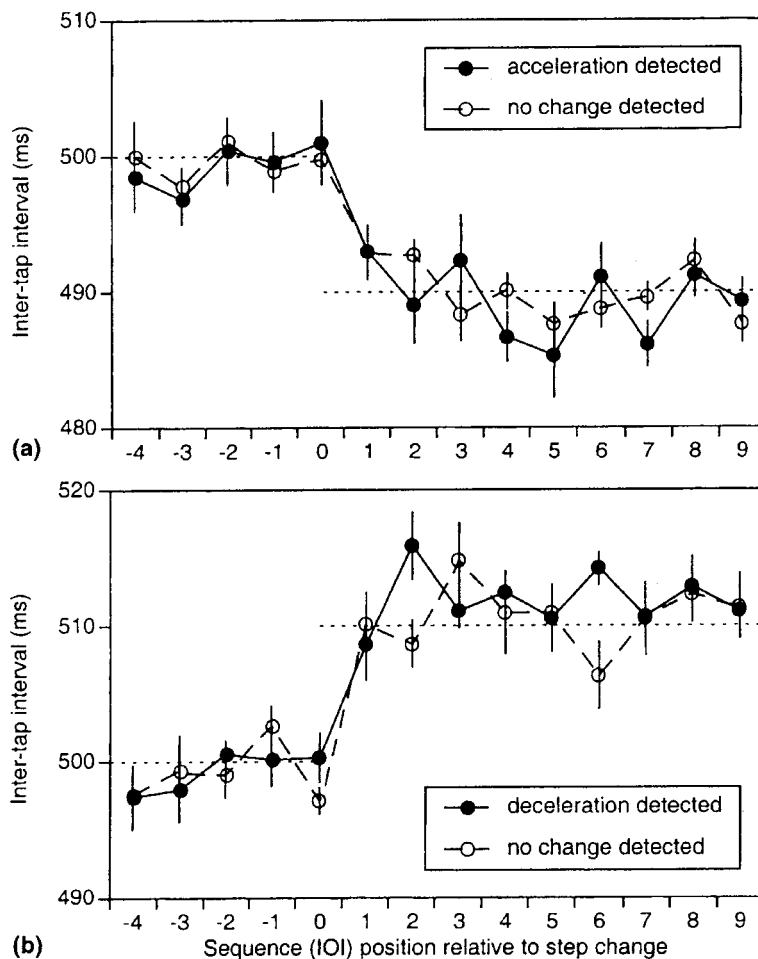


Fig. 3. Average inter-tap interval durations for steps of ± 10 ms as a function of sequence position (step change = 0) contingent on whether or not a step change had been detected, with standard error bars, for (a) negative steps and (b) positive steps (Exp. 1).

were generally close to their expected value, namely $-\Delta t$. Following that point, the behavior of the asynchronies depended very much on Δt : After small step changes ($\Delta t = \pm 5$ or ± 10 ms), the asynchronies remained nearly constant or returned very slowly to the zero baseline. After larger step changes, the asynchronies returned to the baseline more quickly. The relative speed of that return increased with the absolute magnitude of Δt , and it also depended on the direction of the step change, being faster for positive than for negative steps. The relative asynchronies following larger positive steps actually overshoot the baseline. There were considerable individual differences in the extent of that overshoot.

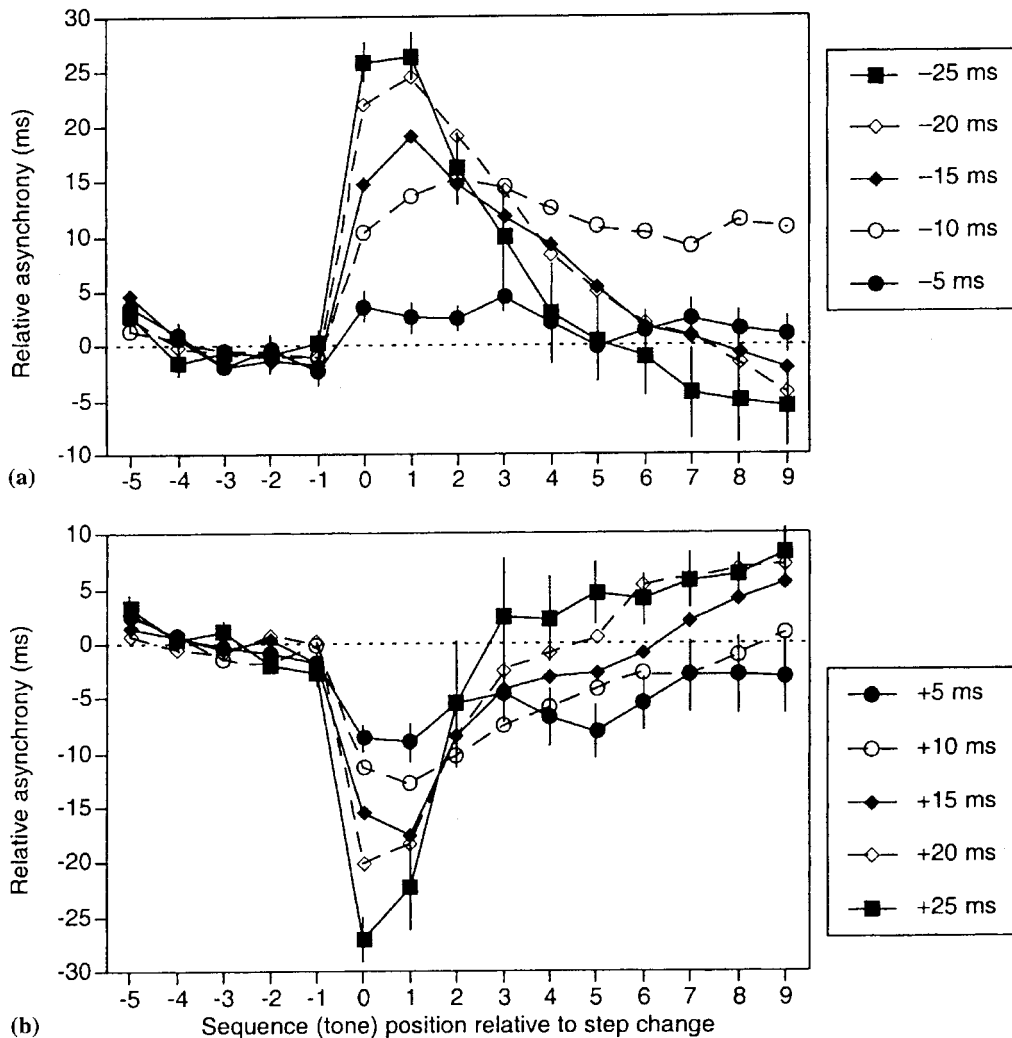


Fig. 4. Average relative asynchronies as a function of sequence position (step change = 0), for (a) negative steps and (b) positive steps (Exp. 1). Standard error bars are shown for the largest and smallest step sizes only.

A three-way repeated-measures ANOVA was conducted on positions 0–9, with the fixed variables of direction (2), magnitude (5), and position (10). The sign of the asynchronies for positive Δt values was reversed, so as to be able to compare directly the time course of adaptation following positive and negative step changes. The main effect of position was of course significant, $F(9, 63) = 38.2$, $p < 0.0001$, due to the average tendency of the asynchronies to return to the baseline. The Magnitude \times Position interaction, $F(36, 252) = 22.9$, $p < 0.0001$, was due to the different time courses of adaptation for

different Δt values. There was also a main effect of magnitude, $F(4, 28) = 4.0$, $p < 0.02$, reflecting the slower adaptation of asynchronies following negative steps than following positive steps; a Direction \times Magnitude interaction, $F(4, 28) = 3.7$, $p < 0.02$, mainly due to the unusually small asynchronies for $\Delta t = -5$ ms; and a triple interaction, $F(36, 252) = 1.6$, $p < 0.03$, due to the faster adaptation and baseline overshoot for large positive Δt values, compared to negative Δt values.

Comparing these results with those of Thaut et al. (1998a), it is again evident that the basic pattern is similar but compressed into a smaller range of Δt values. Their results for steps of ± 10 and ± 20 ms show little change in asynchronies over the first 10 positions following a step change and thus resemble the present findings for step sizes of ± 5 and ± 10 ms. Their results for steps of ± 50 ms closely resemble the present findings for steps of ± 25 ms, and this includes the asymmetric response to positive and negative steps. Again, a plausible explanation for the apparent compression of these patterns into a narrower range of Δt values is that the present participants had a lower detection threshold for tempo changes than those of Thaut et al., which implies that explicit detection was responsible for the more or less rapid change in asynchronies following a step change.

This hypothesis was tested by conducting an analysis on the data for $\Delta t = \pm 10$ ms (see Footnote 6) after dividing the trials of each participant according to whether a tempo change had or had not been detected. Fig. 5 plots these data with standard error bars. Here explicit detection indeed made a difference, especially for positive Δt values (deceleration, Fig. 5(b)): The asynchronies returned towards the zero baseline more quickly when the tempo change was detected than when it was not detected. In the positive step change condition there was even a baseline overshoot when detection had occurred, just as was observed with larger Δt values (Fig. 4(b)). Separate repeated-measures ANOVAS with the fixed variables of response (2) and position (10) showed the Response \times Position interaction to be significant only for positive Δt , $F(9, 63) = 3.8$, $p < 0.0008$. Nevertheless, these data do suggest that conscious awareness of a tempo change affects the time course of the adaptation of asynchronies following a step change. As will be shown now, this probably reflects the dependency of internal period correction on awareness of a tempo change.

Model simulation. Detailed mathematical modeling of the empirical data was considered beyond the scope of this study. However, to demonstrate that the empirical data are largely consistent with the two-process error correction model of Mates (1994a) and with the added hypothesis that period correction

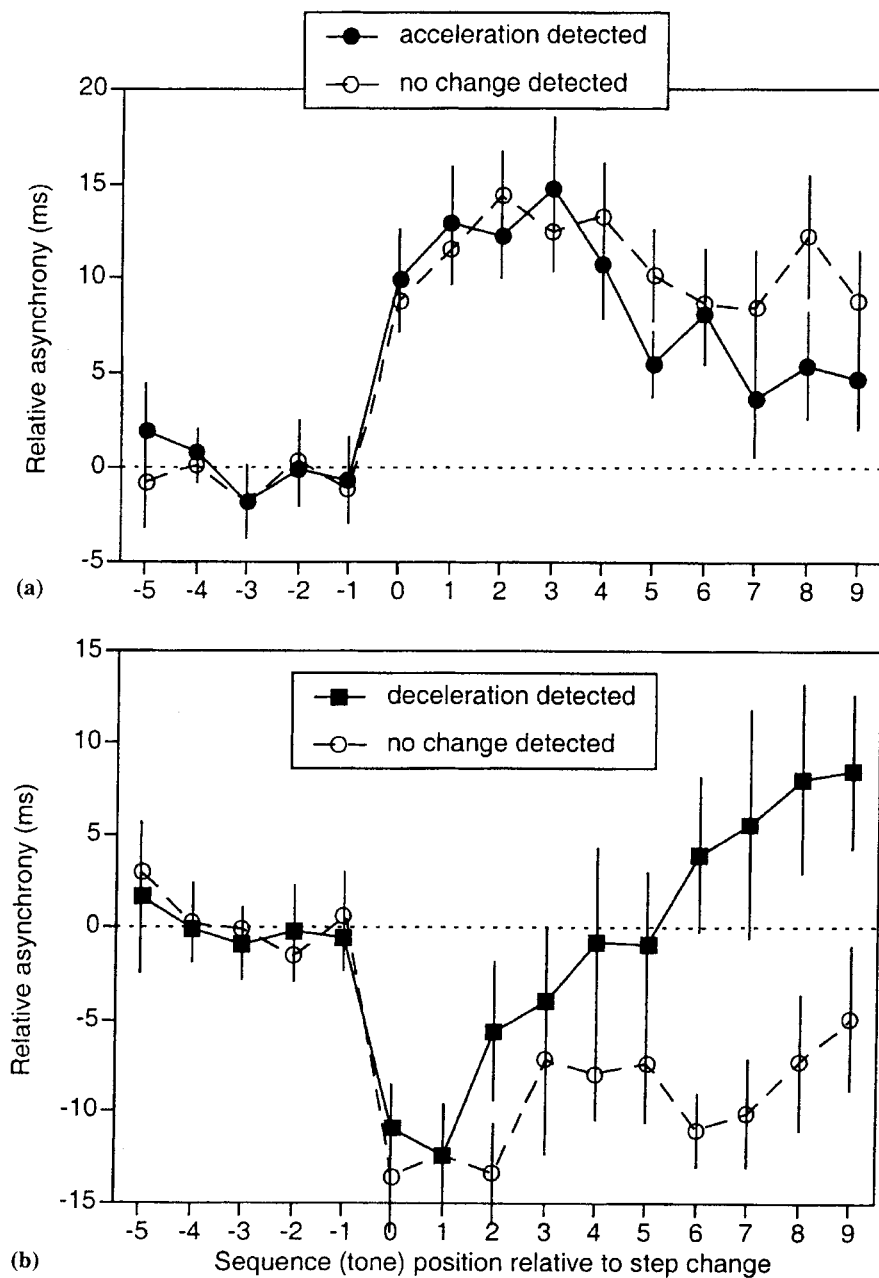


Fig. 5. Average relative asynchronies for steps of ± 10 ms as a function of sequence position (step change = 0) contingent on whether or not a step change had been detected, with standard error bars, for (a) negative steps and (b) positive steps (Exp. 1).

depends on awareness of a tempo change, a simple simulation was conducted using a spreadsheet program (Excel). Mates's model consists of the following two expressions in which upper-case letters indicate time points, lower-case letters indicate intervals, and "I" subscripts indicate internal psychological variables:

$$R_I(k+1) = R_I(k) + t_I(k) - \alpha e_I(k) \quad (\text{phase correction}), \quad (1)$$

which says that the next tap, intended to occur at time $R_I(k+1)$, is made some time after the preceding tap, perceived to have occurred at time $R_I(k)$, and that this time is equal to the timekeeper period $t_I(k)$ minus a proportion α of the most recent synchronization error $e_I(k) = R_I(k) - S_I(k)$, where $S_I(k)$ is the perceived time of occurrence of the last tone; and

$$t_I(k) = t_I(k-1) - \beta[t_I(k-1) - s_I(k-1)] \quad (\text{period correction}), \quad (2)$$

which says that the current timekeeper period $t_I(k)$ is equal to the preceding period $t_I(k-1)$ minus a proportion β of the difference between $t_I(k-1)$ and the last sequence IOI, $s_I(k-1)$. The complete model includes additional terms which are sources of random variability with an expected value of zero; they may be ignored by focusing on expected values, which correspond to data averaged over many trials. The model also includes internal processing delays which are intended to account for the differences between internal and external asynchronies. These delays, too, were ignored by focusing on relative rather than absolute asynchronies. In other words, internal asynchronies and external relative asynchronies were assumed to be identical, as were internal inter-tap intervals and ITIs.

Simulated data resembling the empirical data were generated by holding the phase correction parameter α fixed at 0.6, which is a fairly typical value for IOIs near 500 ms (Repp, 2000; Semjen et al., 2000), and letting the period correction parameter β vary with step size. This strategy was based on the hypothesis that only β depends on awareness of a tempo change, and that awareness (i.e., detectability) increases monotonically with step size. The results of this exercise are shown in Figs. 6 (ITIs) and 7 (asynchronies), which should be compared to the empirical data in Figs. 2 and 4, respectively. The values of β are given in the figure captions. It is evident that the model can account for several important qualitative features of the data: the absence of ITI overshoot for small values of Δt ($\beta < 0.05$), the emergence of ITI overshoot at larger values of Δt ($\beta > 0.2$), the lack of adaptation of asynchronies after small step changes ($\beta < 0.05$), and the increasingly more rapid return of asynchronies to the baseline as step size and β increased. Most interestingly,

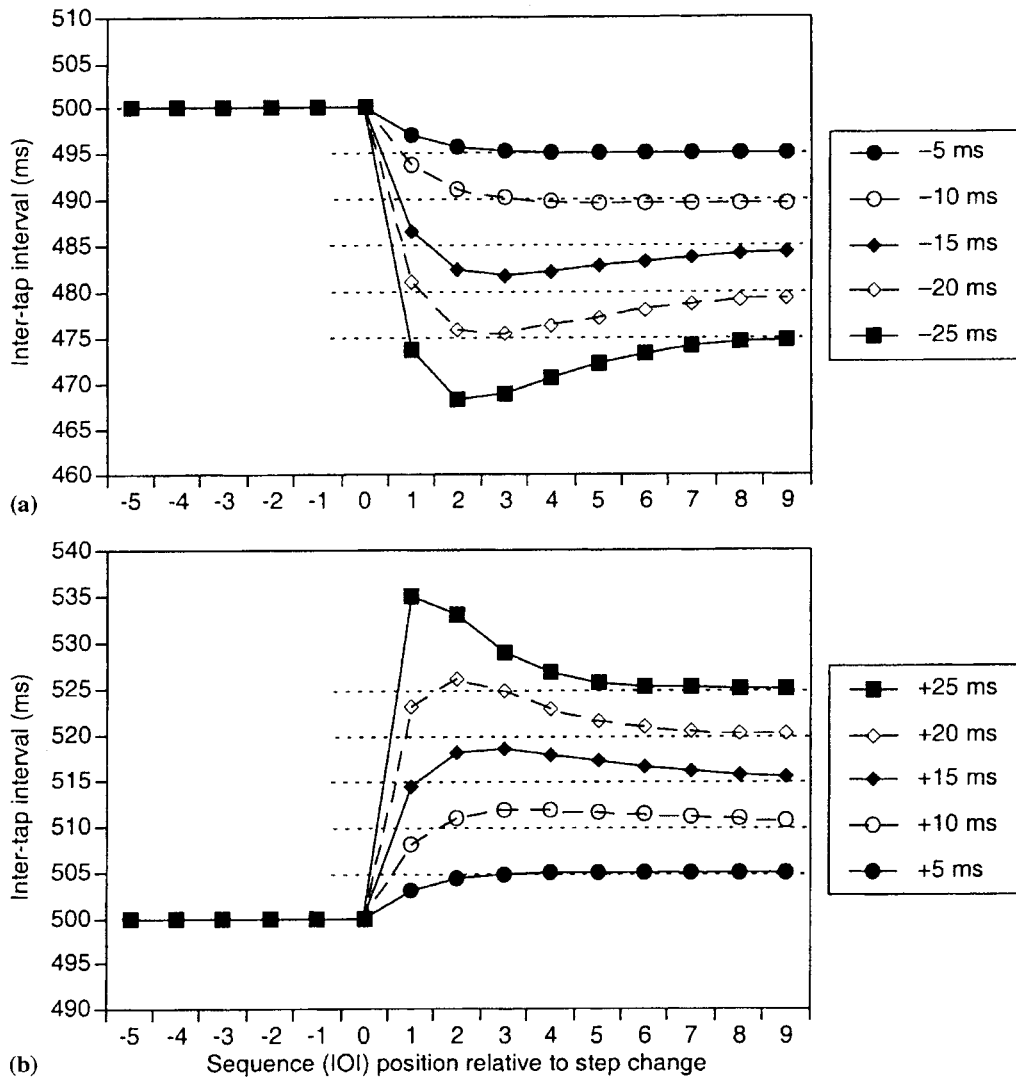


Fig. 6. Simulated inter-tap intervals for (a) negative and (b) positive step changes, generated by the two-process error correction model (Mates, 1994a) with $\alpha = 0.6$, $\beta = 0, 0.03, 0.3, 0.35$ and 0.45 for $\Delta t = -5$ to -25 ms, and $\beta = 0, 0.2, 0.35, 0.55$, and 0.8 for $\Delta t = +5$ to $+25$ ms.

the model makes the non-obvious prediction that, for very small values of β , the slowly adapting relative asynchronies initially should exceed $-\Delta t$; this was indeed observed in at least two conditions ($\Delta t = -10$ and $+5$ ms; see Fig. 4). The asymmetry between the data for positive and negative step sizes was modeled simply by choosing larger values of β for positive step sizes. As it stands, the model cannot account for the finding that relative asynchronies following large step changes tend to overshoot the zero baseline (Fig. 4(b)),

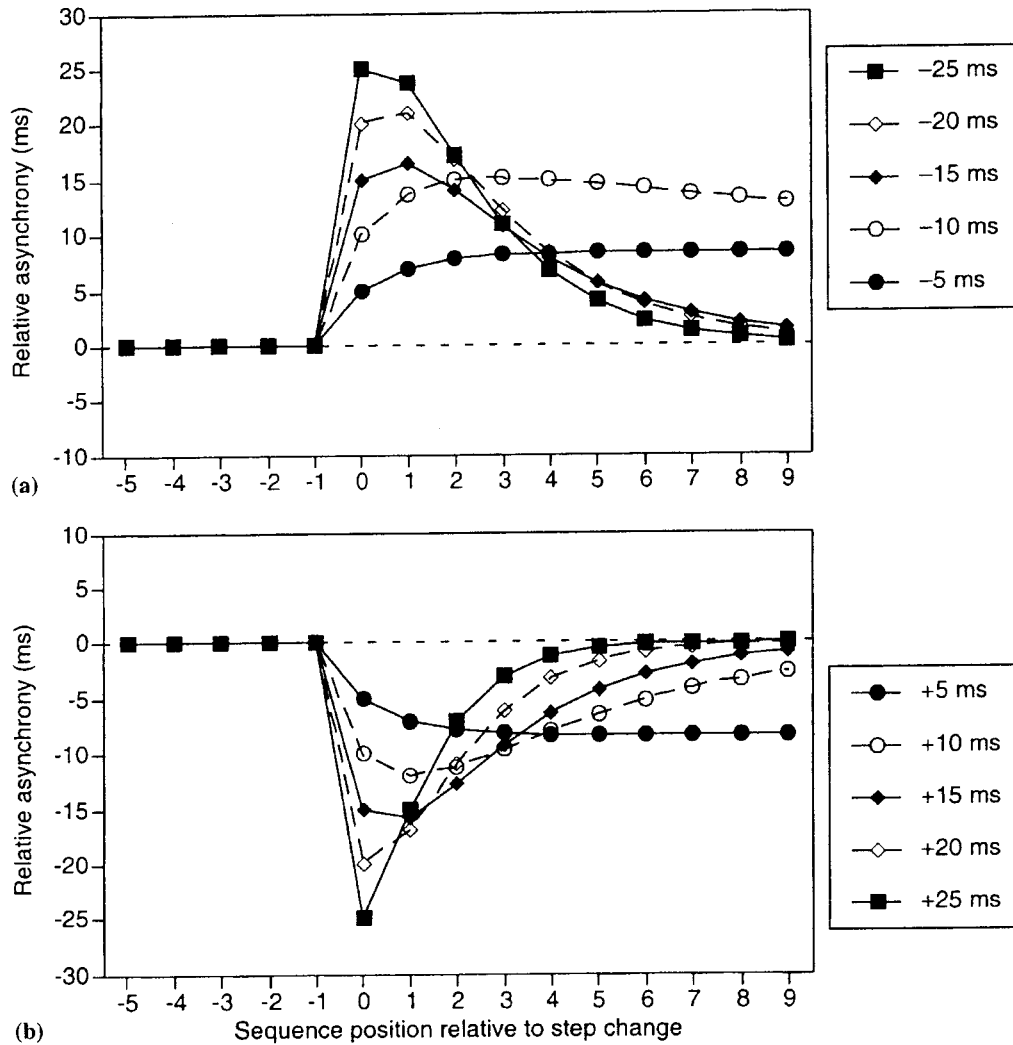


Fig. 7. Simulated relative asynchronies for (a) negative and (b) positive step changes, generated by the two-process error correction model (Mates, 1994a) with $\alpha = 0.6$, $\beta = 0, 0.03, 0.3, 0.35$, and 0.45 for $\Delta t = -5$ to -25 ms, and $\beta = 0, 0.2, 0.35, 0.55$ and 0.8 for $\Delta t = +5$ to $+25$ ms.

and it also underpredicts the ITI overshoot in the second position following larger step changes because such an overshoot is incompatible with a large value of β . Clearly, the model is an oversimplification. (For possible modifications, see below.) As a heuristic tool and first approximation to the data, however, it appears to have considerable merit. In particular, it demonstrates that the changes in observed adaptation patterns could be due to increases in the efficiency of period correction with increasing step size.

According to the main hypothesis of this study, β does not depend directly on step size but rather on awareness of a tempo change, the probability of which increases with step size. Thus, to the extent that there are only two states of awareness (an assumption that may be challenged), there are only two values of β , one (β_u) for undetected tempo changes and another (β_d) for detected tempo changes. The proportion p_d of detected changes increases with step change magnitude, so that the value of β estimated from average data increases as well: $\beta = (1 - p_d)\beta_u + p_d\beta_d$. The simulation suggests that β_u is close to zero, so that effectively $\beta = p_d\beta_d$. However, p_d was greater than zero for the smallest step changes (Fig. 1), which implies a value of β greater than zero. This problem can be partially circumvented by assuming that correct responses to step changes of ± 5 ms represented mostly false alarms. Thus a correction was applied to all p_d values: $p'_d = (p_d - 0.14)/(1 - 0.14)$, with 0.14 being the average p_d for steps of -5 ms. This made the data compatible with the assumption that $\beta_u = 0$, or very nearly so. A problem remains, however, with regard to the value of β_d . The simulation suggests that it is in the vicinity of 0.8 (the value of β suggested by the data for steps of $+25$ ms, which were always detected), but this seems much too high for other step sizes. Even the value of 0.55, suggested by the data for steps of $+20$ ms, is somewhat high compared to the results for negative steps. A good match between $p_d\beta_d$ and the values of β suggested by the simulation can be achieved for all negative steps and for positive steps up to $+15$ ms by assuming that β_d equals 0.4, as shown in Fig. 8. However, a major discrepancy for steps of $+20$ and $+25$ ms must be accepted. Thus, while the results of this exercise are consistent with the hypothesis that period correction depends on awareness of a tempo change, the assumption that the rate of period correction depends solely on awareness seems to be too simple. There seems to be an additional contribution of step change magnitude as such, especially on the positive side.

It would lead too far to explore here the modifications that might be made to the model in order to improve its fit to the data. However, it should be mentioned that p_d increases over the first few IOIs following a step change, as was shown in Experiment 2 (see below). Consequently, the value of β estimated from average data should likewise increase over the first few IOIs. The model could easily provide a better account of the observed initial ITI overshoot by allowing β to vary in this way, and the discrepancy shown in Fig. 8 might also be reduced. Nevertheless, there would still be only two underlying values of β , β_d and β_u .

It has been pointed out earlier that phase correction and period correction in Mates's (1994a) two-process model have identical behavioral manifesta-

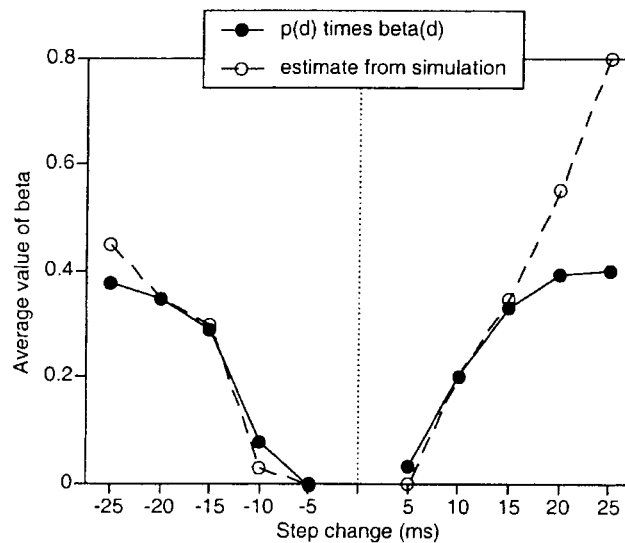


Fig. 8. Average values of the period correction parameter β as a function of step change magnitude, estimated by the product of the proportion of detected step changes (Fig. 1) and a fixed value of β (0.4), versus the β values estimated from simulation of the average data (Figs. 6 and 7).

tions (Repp, 2001). Therefore, exactly the same simulation results could have been obtained by holding β constant and varying α with Δt . Thus the simulation does not prove that it is period correction that improves as Δt increases; it could be phase correction instead. Although earlier findings (Repp, 2000, 2001) indicate that phase correction is unaffected by awareness of temporal change, a direct demonstration that period correction depends on awareness of a tempo change would greatly strengthen the hypothesis pursued here. This was the purpose of Experiment 2.

3. Experiment 2

In part, Experiment 2 was a replication of Experiment 1: It used step changes of the same magnitudes and required detection responses. However, there were three important differences. First, participants were required to continue tapping for a while after each sequence had ended, at what they considered to be the final tempo of the sequence. Since there is no external reference during continuation tapping which could lead to phase or period correction (though tempo drift may occur), the ITIs of continuation tapping were assumed to provide an estimate of the internal timekeeper period at the

end of the sequence. Second, the sequences were terminated at various distances after a step change, ranging from 1 to 8 IOIs. The ITIs of continuation tapping across these various conditions thus were expected to yield an estimate of the time course of internal period correction, which then could be examined contingent on whether or not a step change had been detected. Third, the experiment also included isochronous sequences with IOI durations corresponding to those following step changes, in order to estimate participants' accuracy in reproducing the sequence tempi and to obtain false-alarm rates in the detection task.

3.1. Methods

3.1.1. Participants

There were six participants, four of whom had participated in Experiment 1. Those four included the author, who was musically trained and highly practiced in synchronization tasks, and the three female undergraduates, who had limited musical training, but considerable tapping experience. The two new participants were another female undergraduate (age 19) who, like the others, had some musical training as well as tapping experience, and a female graduate student (age 22) who had no musical training and only limited tapping experience but was able to tap with low variability.

3.1.2. Materials

The sequences consisted of the same high-pitched tones as in Experiment 1 but were of variable length, ranging from 8 to 20 tones. Most sequences contained a single step change after a series of baseline IOIs of 500 ms. The step change occurred either at the 8th or at the 13th tone (i.e., in the 7th or 12th IOI), and Δt ranged from -25 to -5 ms and from $+5$ to $+25$ ms in increments of 5 ms, as in Experiment 1. The sequence ended 0, 1, 2, 4, or 7 tones after the step change; that is, there were 1, 2, 3, 5, or 8 IOIs at the new duration of $500 + \Delta t$ ms (i.e., 475–525 ms). Also included were isochronous sequences consisting of 12 tones, with IOI durations ranging from 475 to 525 ms in 5-ms increments. Each sequence was followed by a silent interval of 5 s and a single lower-pitched tone, which served as the signal to stop tapping. There were 111 sequences altogether ($2 \text{ directions} \times 5 \text{ magnitudes} \times 2 \text{ locations} \times 5 \text{ terminations} = 100$ sequences containing step changes, plus 11 isochronous sequences) which were arranged into five random orders. Each of these five blocks was subdivided into four parts, to provide breaks.

3.1.3. Procedure

Each participant came for three sessions on different days, for a total of about 3 hours. The equipment and procedure were the same as in Experiment 1, except that participants were instructed to continue tapping after a sequence had ended until they heard a lower-pitched tone. They were asked to tap steadily at the final tempo of the sequence. They were informed that most, but not all, sequences contained tempo changes, and that the new tempo could be represented by a variable number of IOIs, including the case of a single IOI. After stopping their tapping, participants reported on the computer keyboard whether they had detected a tempo change and what its direction had been.

3.2. Results and discussion

Because of the partial overlap of Experiment 2 with Experiment 1, it was decided not to carry out the time-consuming analyses of asynchronies and ITIs during synchronization, the results of which were expected to replicate Experiment 1. (Indeed, a full analysis of Experiment 2 would have made Experiment 1 redundant.) Instead, the analysis focused on the detection responses (which now included false-alarm percentages) and the ITIs of continuation tapping.

3.3. Detection responses

The average percentages of detection responses are shown in Fig. 9. They include data for step changes of 0 ms, which derive from isochronous sequences with IOIs of 500 ms. Apart from these additional data, the results were quite similar to those of Experiment 1 (Fig. 1), although there were fewer “no change” responses, somewhat more misidentifications of the direction of change, and a more pronounced asymmetry in favor of positive step changes. If the 50% cross-over points of the correct response functions are taken as estimates of the detection thresholds, then the average thresholds were at –12.5 and –7.5 ms for negative and positive step changes, respectively. The false alarms in response to isochronous sequences indicate that this asymmetry was due to a difference in sensitivity, not response bias: Isochronous sequences were more often misidentified as accelerating than as decelerating. A repeated-measures ANOVA on the correct detection responses with the variables of direction (2) and location (2) revealed only a significant main effect of direction, $F(1, 5) = 9.7$, $p < 0.03$, which confirmed the overall

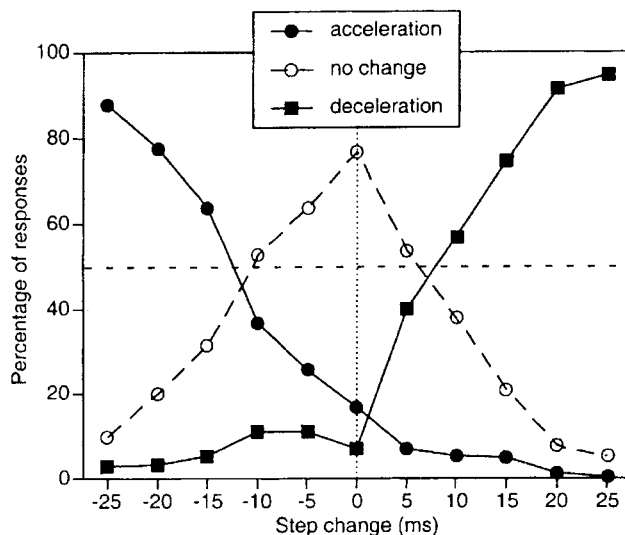


Fig. 9. Average percentages of detection responses as a function of step change magnitude, including false alarms (Exp. 2).

asymmetry. Data from the two locations were combined in all further analyses of the data.

Detectability of a step change depended on the number of IOIs at the new tempo. This is shown in Fig. 10, where the correct detection responses have been broken down accordingly. An ANOVA on these data with the variables of direction (2) and number (5) revealed, in addition to the already mentioned main effects of direction, a strong main effect of number, $F(4, 20) = 45$, $p < 0.0001$. Correct detection responses increased mainly from 1 to 2 to 3 IOIs but little thereafter, which is in agreement with findings of Drake and Botte (1993) on tempo discrimination.

The experiment also included isochronous sequences with IOIs other than 500 ms, which elicited false-alarm responses. The percentages of these responses, together with those of correct “no change” responses, are shown in Fig. 11 as a function of IOI duration minus 500 ms; the data for 500-ms IOIs are duplicated from Fig. 9. False alarms were surprisingly frequent and tended to increase with the deviation of the sequence IOIs from the baseline IOI (500 ms). This suggests that the participants maintained an internal standard of 500 ms, compared the sequence IOIs to that standard, and then sometimes inferred that a tempo change must have occurred because the final tempo was faster or slower than the standard tempo. (False-alarm rates never reached levels suggesting a complete misunderstanding of the instructions.)

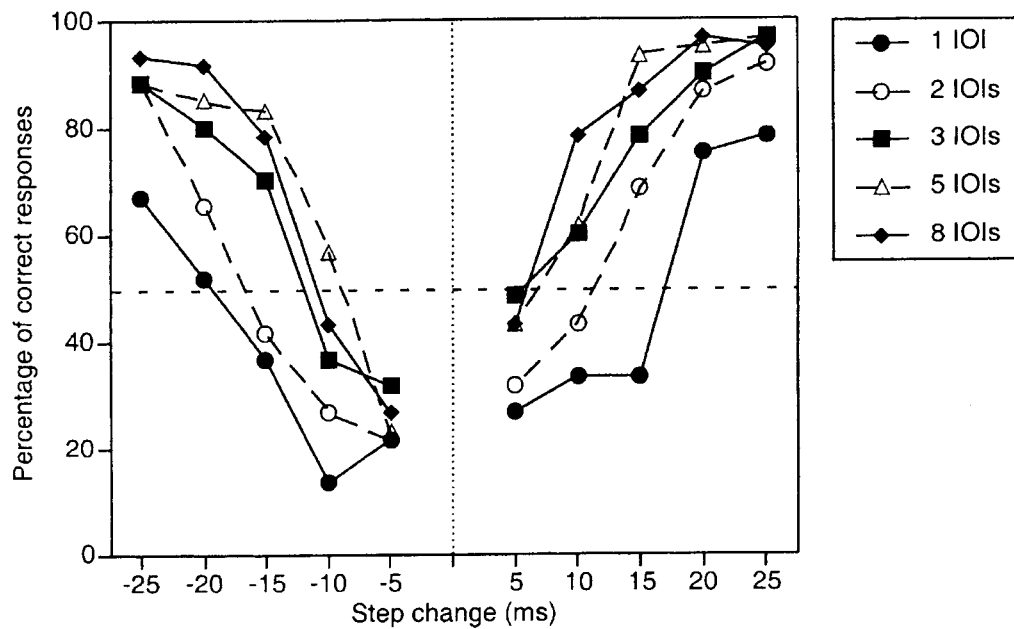


Fig. 10. Average percentages of correct detection responses as a function of step change magnitude and number of IOIs following the step change (Exp. 2).

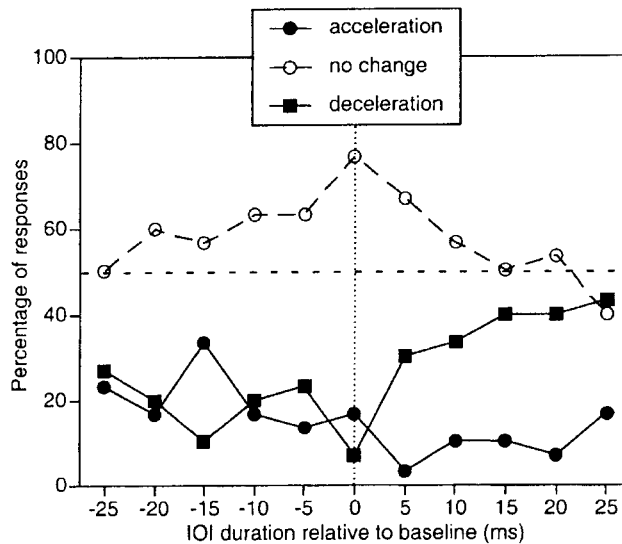


Fig. 11. Average percentages of false-alarm responses to isochronous sequences as a function of IOI duration, relative to the 500-ms baseline (Exp. 2).

Fig. 11 also reveals a strong asymmetry: slow isochronous sequences elicited many more “deceleration” than “acceleration” responses, but fast sequences did not show the opposite difference, except at -15 ms (i.e., 485 ms IOI

duration). An ANOVA on the false-alarm responses (without the responses to 500-ms sequences, and without one participant – the author – who did not commit any false alarms) with the variables of response (2) and direction (2) yielded only a significant main effect of response, $F(1, 4) = 17.1$, $p < 0.02$, due to more “deceleration” than “acceleration” responses. The Direction \times Response interaction fell just short of significance, $F(1, 4) = 7.2$, $p < 0.06$.

The asymmetry in these data, even though it was not quite significant, is consistent with the asymmetry in the correct-response data (Fig. 9). It seems that decelerations were easier to perceive than accelerations (at the baseline tempo used here), regardless of whether they occurred within a sequence or with reference to an internal standard.

3.4. *Inter-tap intervals*

The ITIs during continuation tapping were the main focus of interest. There were generally between 9 and 11 continuation taps. To gain stability, the first 8 continuation ITIs in each trial were averaged to yield an estimate of the timekeeper period. (The first continuation ITI occurred between the first and second continuation taps.) Such averaging would have been problematic, however, if there had been major drifts of tempo during continuation tapping, and especially if these drifts depended on sequence IOI duration (e.g., a regression towards the baseline tempo or towards a preferred tempo). Therefore, the data were first analyzed to determine whether such drifts or interactions occurred. These analyses were conducted on the continuation ITIs following isochronous sequences, which were considered representative of all continuation ITIs. A separate ANOVA was conducted on each participant's data, with the fixed variables of sequence tempo (11) and ITI position (8), and with trials (5) nested within tempi as the random variable. Naturally, each ANOVA yielded a highly significant main effect of tempo, indicating that the continuation tempo varied as a function of sequence tempo. Five of the six participants (the author being the exception) also showed significant main effects of position, $F(7, 308) > 3.0$, $p < 0.005$. These effects were mainly due to a relative lengthening of the first (and, in some cases, also the second) continuation ITI, as had also been observed by Repp (2001, Exp. 1); there was little drift thereafter. The crucial statistic, however, was the Tempo \times Position interaction, which was far from significance for five of the six participants, $F(70, 308) < 1.1$, $p > 0.36$. That is, whatever changes in ITI durations occurred across positions were similar for different tempi. Only one

participant showed a marginally significant interaction, $F(70, 308) = 1.4$, $p < 0.05$, but it was difficult to characterize and was not due to the first ITI. Since the lengthening of the initial ITI(s), where it occurred, added only a small constant bias to the average of the first 8 ITIs, the averaging procedure adopted was considered valid for the present purposes.

The relationship between the average continuation tapping ITIs and the sequence IOIs was examined first for the isochronous sequences only. This was done separately for each participant, and the results are shown in Fig. 12. Despite considerable variability, which is reflected in the standard deviations, it is evident that every participant showed a linear relationship between sequence IOI and continuation ITI durations; there were no hints of any systematic curvilinearity anywhere. For five of the six participants (K.K. being the exception), the slope of the regression line was greater than 1, which indicates an exaggeration of the sequence tempo differences in continuation tapping. Two participants showed marked displacements from the main diagonal (dashed line in Fig. 12), indicating a constant error; the continuation tempo was generally slower than the sequence tempo in one case (B.R.) and faster in the other case (A.S.). The slopes of the regression lines were considered measures of each individual's continuation tapping behavior in the absence of a tempo change in the sequence. It was now hypothesized that a function with the same slope (rather than a slope of 1, which one might have expected naively) should be obtained for continuation tapping following a step change, if that change led to complete period correction. If period correction is incomplete, then a function with a shallower slope should be obtained, and in the absence of period correction the slope should be zero, indicating no influence of the new sequence tempo on continuation tapping.

Consequently, the slopes of the regression lines relating the average continuation ITIs to final sequence IOI duration (or, equivalently, to step change magnitude) were computed separately for each participant and for each number (n) of IOIs instantiating the new tempo following a step change. Fig. 13 shows these slopes as a function of n ("combined", solid lines connecting filled circles). It is evident that the slopes increased as n increased and that they reached an asymptote close to the slope value for isochronous sequences (dashed horizontal line), usually at $n = 5$. Interpreted as estimates of the time course of timekeeper period correction during synchronization following a step change, these curves suggest that period correction is complete after about five taps (in this range of tempi).

In addition, however, it was hypothesized that awareness of a tempo change would play a role. Therefore, the trials were divided into those in

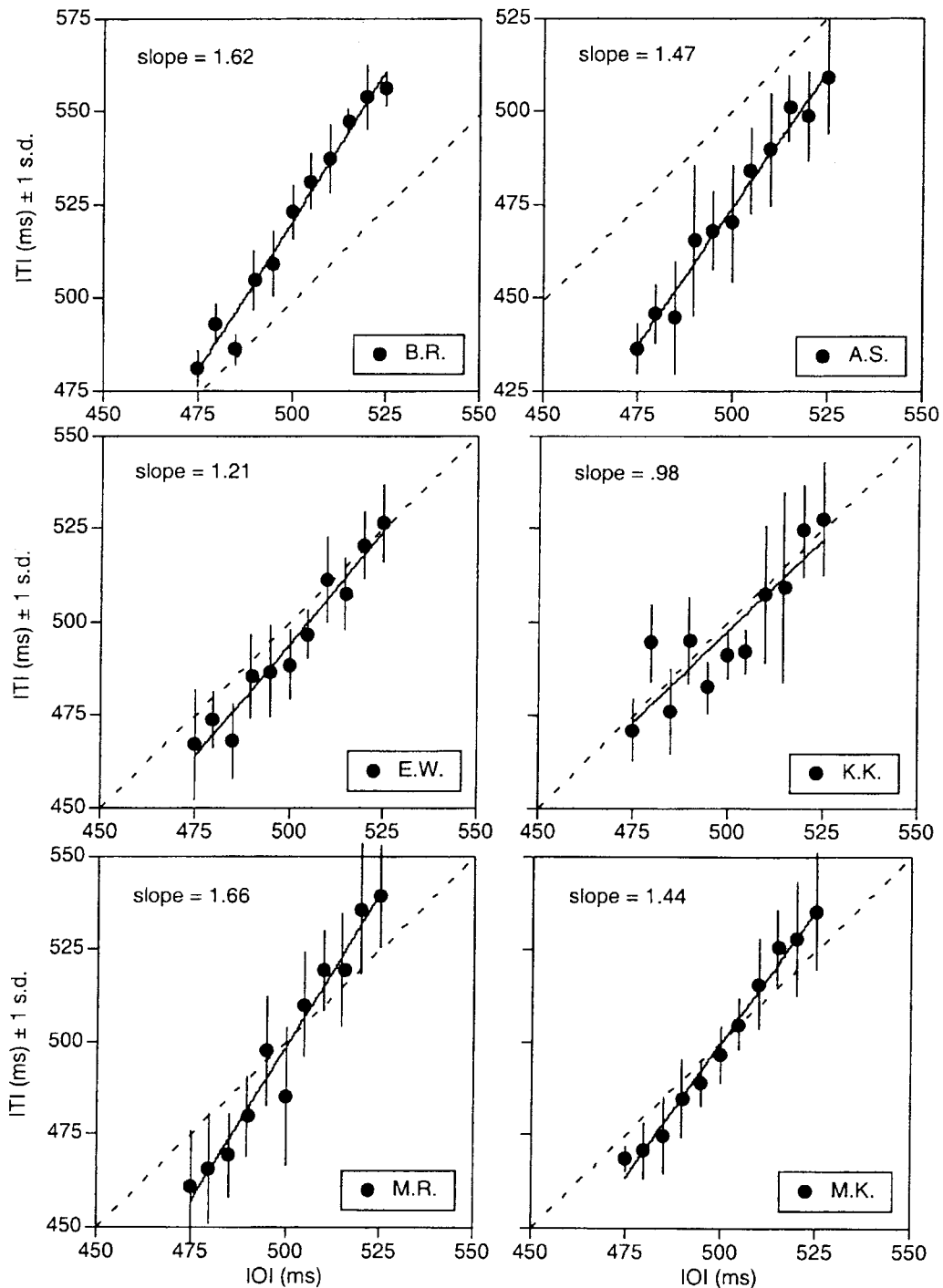


Fig. 12. Average inter-tap intervals in continuation tapping as a function of IOI duration in isochronous sequences, with standard deviation bars, for six individual participants (Exp. 2). Best-fitting regression lines (solid lines), their slopes, and the main diagonals (dotted lines, slope = 1) are also shown.

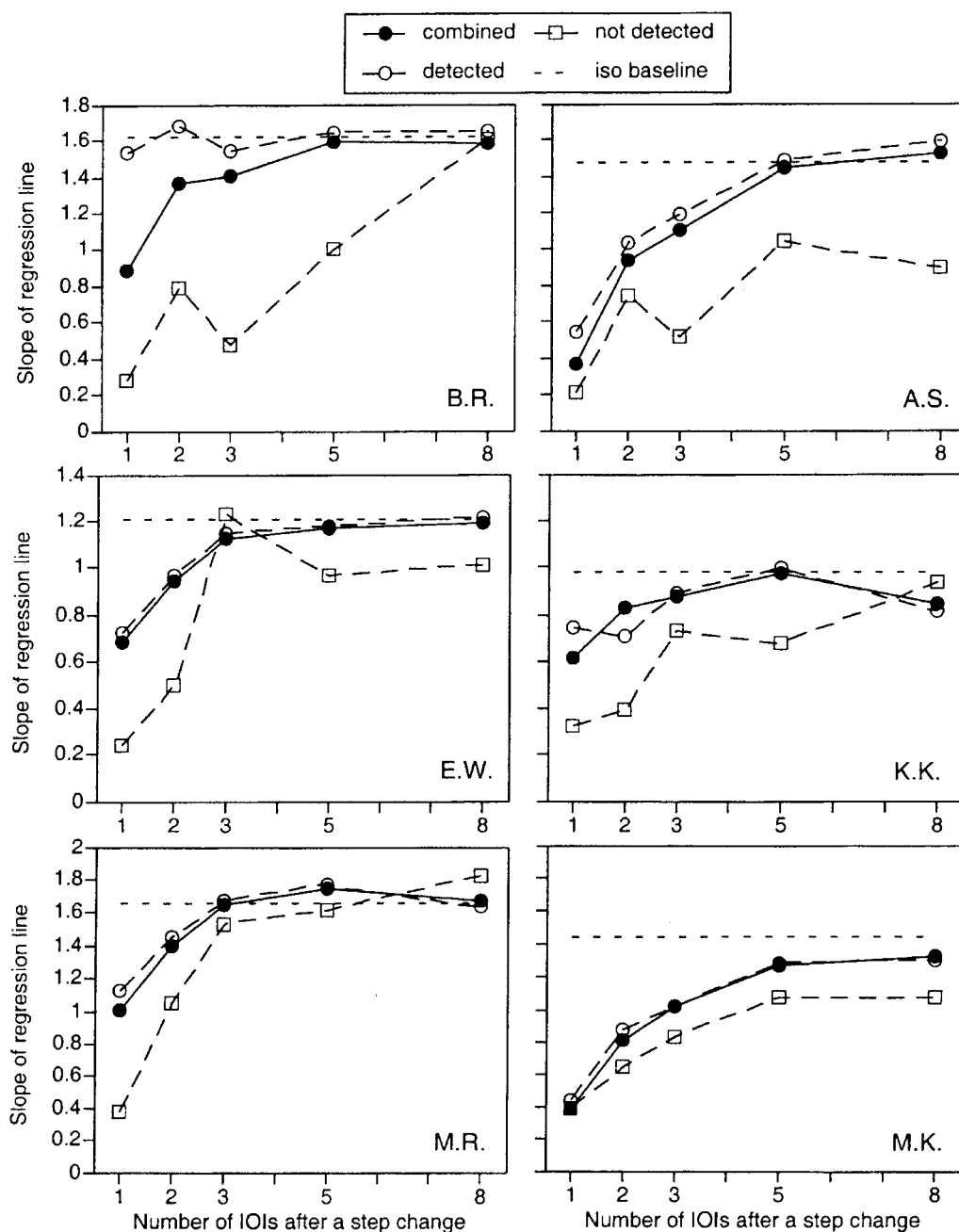


Fig. 13. Slopes of regression lines relating average inter-tap intervals in continuation tapping to IOI duration following step changes, as a function of number of sequence IOIs following the step change, for six individual participants. The functions shown are for all trials combined, for detected step changes, and for undetected or misidentified step changes, respectively. The dashed horizontal line is the slope of the regression line for isochronous sequences (from Fig. 12).

which a tempo change was correctly identified (“detected”) versus those in which no change was heard or the direction of the tempo change was misidentified (“not detected”), and separate regression lines were fitted to the average continuation ITIs derived from these divided data sets. There were a number of missing data points in this analysis, especially in the “not detected” category, because small steps with small n were sometimes never correctly identified in 10 trials, and large steps often were always correctly identified. Also, the 10 trials per condition were often split unevenly; data points representing single trials were excluded. As a result, the slope estimates were less reliable, but they nevertheless yielded a consistent picture. They are shown as the unfilled symbols connected by dashed lines in Fig. 13. It is clear that, for every participant, the slopes were larger – suggesting faster period correction – when the tempo change was detected than when it was not detected or misidentified. The most striking difference was shown by participant B.R. (the author), whose period correction was instantaneous whenever he detected a tempo change (i.e., complete at $n = 1$). This was not the case, however, for the other, less experienced and less musically trained participants.

A summary of the results is shown in Fig. 14. The slope values for detected and undetected step changes were expressed as a percentage of the asymptotic slope derived from the isochronous sequences and then averaged across the six participants. The standard error bars represent between-participant variability. The figure indicates that, on average, period correction was complete at $n = 5$ when a step change was detected, but that it was only 76% complete at $n = 5$ when a step change was not detected. Even at $n = 8$, period correction reached only 87% for undetected step changes, although this value was no longer significantly different from 100%. A repeated-measures ANOVA on the individual slope values (Fig. 13) with the variables of detection (2) and number (5) yielded significant main effects of both variables, $F(1, 5) = 22.4$, $p < 0.006$, and $F(4, 20) = 29.1$, $p < 0.0001$, respectively.

Also shown in Fig. 14 are two theoretical functions (dashed lines without data points) that fit the average data reasonably well. These functions are predicted by the period correction term of the two-process model (Mates, 1994a; see Eq. (2) above and additional simplifying assumptions mentioned there). The functions drawn in Fig. 14 correspond to β values of 0.55 and 0.25, respectively. The fit of the curves is encouraging, but there is a discrepancy between these β values and those arrived at in the model simulation of the data of Experiment 1. The value for detected step changes is somewhat larger than the one estimated earlier (0.4), but in particular the value for

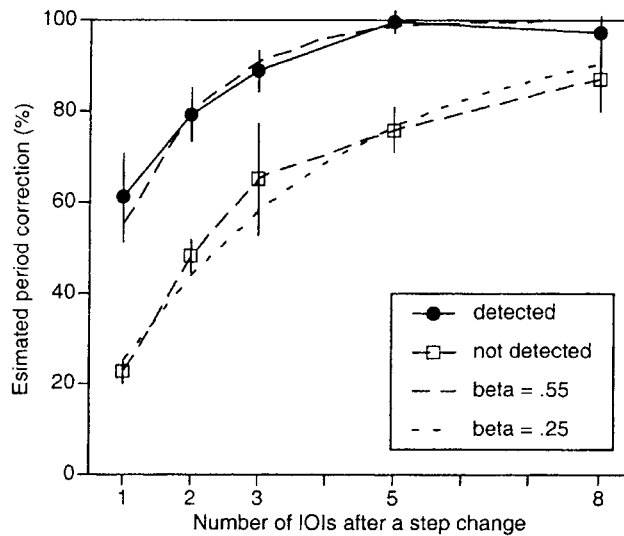


Fig. 14. Average slopes of regression lines relating average inter-tap intervals in continuation tapping to IOI duration following step changes, expressed as a percentage of the slope for isochronous sequences, shown as a function of number of sequence IOIs following the step change, for detected and undetected step changes (Exp. 2). The dotted lines without data points are period correction functions generated by the model of Mates (1994a) with $\beta = 0.55$ and 0.25 , respectively.

undetected step changes is clearly larger than zero. Whereas the previous modeling had suggested that period correction is practically absent following undetected step changes, the present continuation tapping data suggest that period correction does occur, albeit at a slower rate than when the change is detected.

There could be several explanations for this difference in β estimates. One possibility is that the (unanalyzed) synchronization data of the present experiment differed from those of Experiment 1 in being more compatible with such a larger β value for undetected trials. This seemed relatively unlikely and would have required a considerable investment of time and effort to check out. Another possibility is that the β value for undetected step changes was overestimated in Experiment 2 because trials were included on which a step change had been detected but misidentified. This was investigated by excluding these trials and recalculating the slopes of the regression lines for several participants. There was little difference, except for increased variability due to data attrition. A third possible explanation is that participants adopted a more conservative criterion than in Experiment 1 in making their detection responses, so that the “undetected” category actually included trials on which a step change was detected but not reported. This, too, seems

somewhat unlikely, at least for participants like B.R. (highly experienced) and E.W. (very low threshold). A fourth, theoretically more interesting explanation might be that the tempo of continuation tapping depends not only on the internal timekeeper period but also on the immediately preceding ITIs during synchronization which, as Experiment 1 has shown, adapt rapidly to a new sequence tempo regardless of the detectability of the change – a phenomenon attributed primarily to phase correction. In other words, a tendency to continue tapping at the same overt tempo may compete with the tendency to tap at the tempo prescribed by the internal timekeeper period. Such a persistence of the overt tempo should in principle be short-lived, and the tempo of continuation tapping therefore should exhibit a drift towards the baseline tempo; however, no such drift was observed. Finally, it is conceivable that a memory for the immediately preceding ITI duration affects the setting of the timekeeper period as soon as continuation tapping starts. Such an interaction would result in a stable continuation tapping tempo and would lead to an overestimation of β . However, it is not clear whether this is a plausible assumption. This issue requires further investigation and will have to remain unresolved for the time being.

4. General discussion

The present study had three main goals: to replicate the intriguing results of Thaut et al. (1998a), to interpret them in terms of two underlying error correction processes (Mates, 1994a), and to provide evidence that internal period correction is dependent on conscious awareness of a tempo change. On the whole, the study was successful on all three counts, even though some unanswered questions remain.

Experiment 1 replicated the findings of Thaut et al. (1998a) in all their salient aspects: Following small step changes, ITIs adapted quickly but asynchronies adapted slowly. Following larger step changes, both ITIs and asynchronies adapted fairly quickly, but ITIs showed initial over-correction which was more pronounced for positive than for negative step changes. After larger positive steps, there was also a tendency for asynchronies to overshoot the baseline. The only major difference from the results of Thaut et al. was that the transition from one pattern of adaptation to the other occurred at smaller step change magnitudes. Experiment 1 also included a detection task which confirmed results in the literature indicating that the detection threshold for tempo changes is near 2%, and showed that the

threshold for positive steps is lower than that for negative steps (a result confirmed by Experiment 2). The detection thresholds coincided approximately with the transition between adaptation patterns, which led to the hypothesis that awareness of tempo changes plays a role in adaptation to these changes. It also led to the (unverifiable) suggestion that the later transition point in the data of Thaut et al. may have been due to higher detection thresholds in their participants. An analysis of the data of Experiment 1 contingent on whether or not a step change was detected provided some support for the awareness hypothesis, mainly for adaptation of asynchronies following positive step changes.

Thaut et al. (1998a) did not explain their findings in terms of underlying internal processes. Rather, they referred only to observable quantities: the IOIs (sequence period), asynchronies (relative phase of taps and tones), and ITIs (tapping period). Thus they concluded that small step changes are followed by rapid period correction but slow phase correction, meaning that ITIs adapt quickly but asynchronies adapt slowly to the new tempo. In terms of internal processes of phase and period correction, however, there are two possible interpretations of this finding, one corresponding to that given by Thaut et al., and the other being just the opposite. Due to the symmetric roles of phase and period correction in Mates's (1984a) model (Repp, 2001), these two contrasting interpretations cannot be distinguished by modeling alone. However, earlier data (Repp, 2000, 2001, *in press-b*) have suggested that phase correction is a rapid and automatic process that is independent of awareness. Therefore, the fast period correction (= ITI adaptation) referred to by Thaut et al. was attributed to fast internal phase correction, whereas the slow phase correction (= asynchrony adaptation) referred to by Thaut et al. was attributed to slow internal period correction. This may seem paradoxical, but it really is not; only the overlap in terminology is confusing. Here the term "adaptation" has been used to describe a change in observable quantities, while the term "correction" has been reserved for describing a change in internal variables. Moreover, the terms "phase" and "period" have been avoided when referring to asynchronies and ITIs, respectively.

It was hypothesized that the speed of internal period correction increases with step change magnitude because (a) larger step changes are more likely to be detected, and (b) detected step changes lead to faster period correction than undetected changes. The first assertion is obviously true, but with the important corollary that the probability of detection also increases with the number of IOIs at the new tempo (up to at least 3), as shown in Experiment 2. The second assertion received support in Experiment 2, where it was

shown that the tempo of continuation tapping following a step change reflects the new sequence tempo to a greater extent when the tempo change was detected than when it was not detected. If the assumption is correct that the ITIs of continuation tapping reflect directly the internal timekeeper period at the end of the sequence, then the results of Experiment 2 show that period correction is faster after detected than after undetected tempo changes. Consequently, the faster period correction after larger than after smaller step changes, which was inferred from the application of the two-process model to the data of Experiment 1, may be due to the higher proportion of detected changes, which are associated with faster period correction.

Although roughly consistent with the data, this hypothesis encountered two difficulties. First, the modeling of the data of Experiment 1 suggested that period correction following large positive step changes was more effective than could be explained by the hypothesis. It is possible that step change magnitude has a direct influence on period correction, above and beyond the effect of detecting a tempo change. Second, the modeling of the data of Experiment 1 suggested that there was very little internal period correction following undetected step changes, whereas the continuation tapping data of Experiment 2 indicated that slow period correction did occur. Period correction following detected step changes was also estimated to be faster in Experiment 2 than in Experiment 1. These discrepancies remain unexplained for the time being. Clearly, the quantitative fit of the two-process error correction model to the data is not yet good, and additional parameters may be necessary. Nevertheless, the model does provide a useful conceptual framework for further explorations of the complexities of sensorimotor synchronization.

Surely the most important finding of this study is that period correction is affected by awareness of temporal change, whereas phase correction seems to be insensitive to such awareness. This differential relation of the two error correction processes to consciousness may provide a useful diagnostic for distinguishing them in future behavioral and especially neuropsychological studies. Phase correction appears to be a more encapsulated process than period correction, though it remains to be seen what exactly that corresponds to in terms of brain function. I have speculated elsewhere (Repp, *in press-a*) that the period correction process, being accessible to top-down influences, is also involved in temporal expectations and temporal pattern learning. In other words, temporal knowledge may be expressed through top-down modulations of the internal timekeeper period, whereas phase correction may be a purely bottom-up, stimulus-bound process.

There may be a simple explanation of why phase correction is a lower-level process than period correction: phase correction mainly operates on times of occurrence (taps, tones) and their differences, whereas period correction operates on intervals (timekeeper period and IOIs) and differences between intervals. Thus, period correction is concerned with the first derivative of the incoming and outgoing time series, which requires memory for at least one preceding event. This greater computational complexity probably calls for greater neural resources, thus making the process more extensive in brain space and in time, and hence more accessible to higher-level cognitive processes.

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