Psychological Research (2000) 63: 106–128

ORIGINAL ARTICLE

Bruno H. Repp

Compensation for subliminal timing perturbations in perceptual-motor synchronization

Received: 19 November 1998 / Accepted: 18 March 1999

Abstract It is sometimes assumed that limits of temporal discrimination established in psychophysical tasks constrain the timing information available for the control of action. Results from the five perceptual-motor synchronization experiments presented here argue against this assumption. Experiment 1 demonstrates that subliminal (0.8–2%) local changes in interval duration in an otherwise isochronous auditory sequence are rapidly compensated for in the timing of synchronized finger tapping. If this compensation is based on perception of the highly variable synchronization error (SE) rather than of the local change in stimulus period, then it could be based solely on SEs that exceed the temporal order threshold. However, that hypothesis is ruled out by additional analyses of Exp. 1 and the results of Exp. 2, a combined synchronization and temporal order judgment task. Experiments 3–5 further show that three factors that affect the detectability of local deviations from stimulus isochrony do not inhibit effective compensation for such deviations in synchronized tapping. Experiment 5, a combined synchronization and detection task, shows directly that compensation for timing perturbations does not depend on explicit detection. Overall, the results suggest that the automatic processes involved in the temporal control of action have access to more accurate timing information than do the conscious decision processes of auditory temporal judgment.

Introduction

The perception of sensory information is subject to limits that have been established in many psychophysical experiments. Although it is now generally accepted that perceptual thresholds are subject to variable response criteria operating on a continuum of sensory information (Green & Swets, 1966), the assumption is still widespread that sensory input below the conscious detection threshold is of little use to the organism. Indeed, there are limits to the resolution of the various sense organs that restrict the information that can be acquired from the environment. In the case of temporal information, however, there is no specific sense organ and hence no obvious limit to sensory resolution. Nevertheless, small temporal differences often are not detected by perceivers. The present study investigated whether these small, subliminal differences are nevertheless registered and made use of in controlling the timing of motor behavior.

The task of interest here is perceptual-motor synchronization with a sequence of auditory stimuli. In the relevant literature it has been repeatedly assumed that psychophysical detection thresholds limit the accuracy of error correction in synchronization. This assumption may be seen as a manifestation of the more general (often implicit) view that conscious decisions intervene between sensory information processing and action (see Neumann, 1990). The perceptual threshold that is usually invoked is the temporal order threshold, since the crucial variable in a synchronization task is the difference between the perceived times of occurrence of a response (such as a finger tap) and of a pacing stimulus (such as a tone). This is the subjective synchronization error (SE) or phase error, which is to be minimized through a process of error correction. Michon (1967) was perhaps the first to hypothesize that "if the [synchronization] error is smaller than a threshold value below which it cannot be detected or below which it is not possible to perceive the direction of the error (Hirsh & Sherrick, 1961), no action will be taken" (p. 84). In his own research, Michon employed several methods of perturbing the temporal regularity of an auditory pacing stimulus. However, the perturbations were generally above the detection threshold, so that the participants responded to temporal changes they could hear.

B. H. Repp
Haskins Laboratories, 270 Crown Street,
New Haven, CT 06511-6695, USA;
Tel.: (203) 865-6163; Fax: (203) 865-8963;
E-mail: repp@haskins.yale.edu

Michon's threshold hypothesis has been reiterated or stated independently by several other authors concerned with perceptual-motor synchronization, including Voillaume (1971), Mates (1994b), Vorberg and Wing (1996), and Thaut, Miller, and Schauer (1998a). Only Mates (1994b), however, actually implemented the assumption in a formal model of error correction and showed that this model accounted well for some earlier data in the literature. However, he did not directly compare the results of his simulation with one based on a model that does not incorporate such a threshold assumption (Mates, 1994a). Other researchers, such as Hary and Moore (1985, 1987), Pressing (1998), and Large and Jones (1999), do not refer to perceptual thresholds, but neither do they discuss why they find them irrelevant.

The perceptual threshold for temporal order seems well established. Classic research by Hirsh (1959) has demonstrated that an onset asynchrony of about 20 ms is necessary for listeners to identify the order of two different sounds correctly 75% of the time (50% being chance). The threshold for detecting that two auditory event onsets are not simultaneous is much smaller, but the specific order of the two sounds cannot be recognized at such short intervals. The temporal order threshold has been found to be about the same in different modalities and even across modalities, including the auditory-tactile combination (Hirsh & Sherrick, 1961). Since the average asynchrony in perceptual-motor synchronization tasks is usually negative, meaning that the finger tap tends to precede the stimulus (see, e.g., Aschersleben & Prinz, 1995), it must be assumed that the average asynchrony represents a point of subjective simultaneity (PSS) and that the temporal order of stimulus and response is perceived relative to the PSS (see Mates, 1994a).[1] However, neither the PSS nor the temporal order threshold has ever been determined in a synchronization task by requiring explicit judgments about the SE. (Experiment 2 of the present study addressed this issue.)

To maintain synchrony with a stationary (isochronous) stimulus sequence, all that is required is a process of phase error correction which modifies the intervals generated by an internal timekeeper without changing the underlying timekeeper period (Vorberg & Wing, 1996; Semjen, Vorberg & Schulze, 1998; Pressing, 1998, 1999). In synchronization with nonstationary or perturbed sequences, however, an additional process of period correction may be required (Mates, 1994a; Thaut et al., 1998a). In fact, Michon (1967) proposed a model that assumed period correction only, with the consequence that the response timing echoes the stimulus timing. Surprisingly, authors concerned with period correction have made no reference to the interval discrimination threshold, which constrains the explicit detection of a change in stimulus period. Auditory interval and tempo discrimination thresholds have been established in many psychophysical studies. For interval durations between 300 and 1000 ms, Weber's law seems to hold approximately (see Friberg & Sundberg, 1995). Although the threshold depends on the paradigm used and on the training of the participants, detection thresholds are rarely below 4% for changes in single intervals or event onsets in a sequence (Hibi, 1983; Halpern & Darwin, 1982; Clarke, 1989; Drake, 1993; Repp, 1999a) and rarely below 2% for sudden changes in event rate or tempo (Drake & Botte, 1993; McAuley & Kidd, 1998).

Thus, there are really two threshold hypotheses, which in the following will be called TH1 and TH2. They refer to different kinds of perceptual information that gives rise to error correction. TH1 states that error correction in synchronization is limited by the temporal order discrimination threshold which constrains perception of the SE, whereas TH2 states that error correction is limited by an interval (or tempo) discrimination threshold that constrains the perception of changes in stimulus interval duration (or tempo). In each case, the perceptual threshold is taken to be a point on a representative psychometric function generated by explicit judgments in a psychophysical experiment. Since that point represents imperfect accuracy (usually 75% discrimination or 50% detection), the threshold hypotheses predict imperfect error correction not only below but also at and even somewhat above the respective thresholds.

TH1 is more difficult to assess than TH2 because the SE is highly variable due to the variability of the motor response (which at moderate and slow tempi is due mostly to the central timekeeper controlling it; see Wing & Kristofferson, 1973), whereas a change in stimulus period is computer-controlled and hence virtually error-free. Of course, both variables must undergo auditory processing, and this may introduce perceptual noise (see Mates, 1994a). Indeed, it is presumably such perceptual noise that is responsible for the existence of perceptual thresholds for interval duration and temporal order. Therefore, one way of phrasing the question addressed in the present research is whether the motor control system has access to less noisy temporal information than does explicit judgment.

It is often not clear whether the adaptive motor response following a stimulus perturbation involves phase error correction, period correction, or both. Since any perturbation of stimulus timing affects both stimulus period and phase (at least, locally) and any motor adjustment likewise affects both response period and phase (at least, locally), period and phase error corrections cannot be distinguished at the behavioral surface. However, the two-level model of motor timing proposed by Wing and Kristofferson (1973) and applied to synchronization by Vorberg and Wing (1996) makes the

[1] The term asynchrony is used here to refer to an objective measurement, whereas the terms SE and phase error refer to the subjective divergence of stimulus and response. Pressing and Jolley-Rogers (1997) express the opinion that the negative asynchrony limits the impact of the temporal order threshold, implying that the average asynchrony does not represent the PSS, which is probably mistaken.

crucial assumption that phase error correction can occur independently of period correction, by means of local adjustments to intervals generated by a central timekeeper.[2] This assumption is also relevant to the distinction between TH1 and TH2. It seems plausible that phase error correction would be based only on information about the SE, whereas period correction would be based only on information about a change in stimulus period and/or a mismatch between timekeeper and stimulus periods. Thus, the two different kinds of perceptual information may feed into two different error correction mechanisms.

There are already data in the literature suggesting that TH2 does not hold. For example, Hary and Moore (1985) presented participants with long auditory sequences in which runs of 30 inter-onset intervals (IOIs) alternated between durations of 695 and 705 ms, a stimulus period difference of about 1.4% that is below the tempo discrimination threshold reported by Drake and Botte (1993). Nevertheless, statistical analysis of the data showed that the participants adjusted the period of their response to the changes in the stimulus sequence. In a subsequent study, Hary and Moore (1987) presented nonstationary click sequences whose IOIs either varied randomly around 700 ms or rapidly alternated between two durations. Both types of changes were described as subliminal.[3] Although the results were not presented in detail, there was again statistical evidence that the participants' motor responses adapted to the stimulus changes.

Additional evidence against TH2 comes from recent research by Michael Thaut and colleagues. Like Hary and Moore (1985), Thaut et al. (1988a) investigated synchronization to sequences containing step changes in IOI duration (i.e., tempo changes), the smallest of which (2%) was in the vicinity of the tempo discrimination threshold. Thaut et al. found that the response period adjusted to these small changes in stimulus period within a few taps, whereas the phase errors created by the tempo changes were corrected much more gradually. Larger (suprathreshold) step changes, however, elicited a correction process that both adjusted the response period and quickly restored the original phase relationship through initial overcorrection of the response IOI (as shown previously by Michon, 1967). While the major conclusion of Thaut et al. was that step changes of different magnitude elicit different adaptive strategies, perhaps contingent on participants' awareness of a tempo change, they also made the point that changes in stimulus period that are difficult to detect are nevertheless compensated for. Moreover, a related magnetoencephalographic study found evidence of primary auditory cortex activity in response to tempo differences of 2% (Tecchio et al., 1998).

Thaut, Tian, and Azimi-Sadjadi (1998b) used stimulus sequences whose period (400–600 ms) was regularly perturbed by alternately increasing and decreasing every other interval by amounts ranging from 1% to 7%. They found that the response IOIs echoed the stimulus IOIs at a lag of one, as Michon (1967) had found for larger modulations. They also collected some psychophysical data which showed that the 1% and 3% modulations were below the detection threshold. To the extent that the adaptive response adjustment reflects a period correction mechanism, these data provide strong evidence against TH2. However, a continuous phase error correction process (Vorberg & Wing, 1996; Semjen et al., 1998; Pressing, 1998, 1999) could possibly produce the same result, and in that case the results may bear on TH1 rather than TH2.

The immediate stimulus for the present investigation came from a previous study (Repp, 1999a: Exp. 2) in which participants tapped their finger in synchrony with an excerpt of piano music. The experiment employed a perturbation method that, for one reason or another, has rarely been used in synchronization research: the lengthening or shortening of a single interval, effectively a phase shift. (Michon, 1967, called this a "pulse" change.) The music was played under computer control such that 32 of its 36 IOIs were constant at 500 ms, while 4 randomly chosen IOIs (separated by at least 4 unchanged IOIs) were lengthened by either 20 or 40 ms (4% or 8%).[4] A previous detection experiment using the same materials (Repp, 1998a: Exp. 1) had established that 40-ms increments were detected by musically trained listeners about 70% of the time, whereas 20-ms increments were detected only about 40% of the time. Moreover, the detectability of these changes varied greatly according to their position in the music. In the synchronization task, however, it was found that participants rapidly compensated for the IOI increments by lengthening the following tap IOI by 20 or 40 ms, on the average. The rapidity of this compensation was independent of the magnitude of the timing perturbation and of its position in the music. At the time, the distinction between TH1 and TH2 had not been drawn, and the conclusion was simply that the error correction process was not contingent on explicit detection of a change in stimulus timing (i.e., TH2).

The aim of the present research was to provide even stronger evidence that subliminal timing perturbations of the pulse type are compensated for in synchronized tapping. To that end, Exp. 1 employed pulse change magnitudes that were well below the explicit detection threshold, and Exps. 3–5 varied factors that are known to influence the detection threshold, to investigate

[2] Note, however, that a period correction does affect the phase error.

[3] Hary and Moore (1985) did not report the magnitude of the variation. Their Fig. 1 suggests a standard deviation of 12 ms in the random condition. The durations in the alternating condition may have been again 695 and 705 ms, but it is not clear whether they alternated randomly or regularly, as in Hary and Moore. Hary and Moore also did not discuss their motivation for employing subliminal timing differences; however, see Wing (1977a) for a good rationale.

[4] It was only for reasons of economy that there were four changes per sequence. Sequential effects are not believed to have played an important role.

whether they affect the rapidity and completeness of motor compensation. Experiment 5 used a combined synchronization and detection task to examine directly whether compensation for pulse changes in the vicinity of the detection threshold is contingent on awareness of a change in timing (i.e., TH2).

The conceptual distinction between TH1 and TH2 emerged only in the course of this research, and it became increasingly clear that the results of the experiments pertained more to TH1 than to TH2 (though possibly to both). Although it is possible in theory that compensation for a pulse change is in the form of a local adjustment of the timekeeper period that helps restore the correct phase (TH2), a more plausible compensation strategy would be to adjust the relative phase of the motor response (TH1) without any change in the timekeeper period that paces the motor activity (Vorberg & Wing, 1996). This raised the crucial question of whether compensation for subliminal stimulus perturbations is mediated by supraliminal SEs created by large response variability. Additional analyses of the data from Exp. 1 were conducted to address this point, and Exp. 2 (chronologically last) investigated the explicit temporal order threshold for cross-modal SEs in the synchronization paradigm.

The method of data analysis employed here was to average over many trials and thereby to extract a hypothetical underlying "compensation function" (asynchrony as a function of position in the sequence) from the substantial noise that afflicts the timing of motor responses. This approach contrasts with the time-series analysis methods and statistical modelling often used in studies of tapping and synchronization, but it seems more appropriate when stimulus perturbations are nonrandom and local (see also Michon, 1967; Thaut et al., 1998a). Nevertheless, the shapes of the compensation functions may have implications for formal models of error correction that will be touched upon.

Experiment 1

Experiment 1 used simple tone sequences containing pulse changes that were well below the interval discrimination thresholds reported in the literature. The questions were whether these changes would be compensated for in the synchronized motor response, and if so, whether the compensation was based on SEs that exceed the temporal order threshold.

Method

Participants. There were eight participants. Six were paid volunteers ranging in age from 19 to 33; in addition, a research assistant (age 37) and the author (age 53) participated. Except for one undergraduate student who had had voice lessons for 5 years, all participants had received at least 10 years of musical instruction and played instruments or sang at fairly advanced levels. It was hoped that their musical experience would help reduce variability.

Stimuli. The stimuli were sequences of 50 short tones with a baseline IOI of 500 ms. Each tone was the high-pitched note C_8 (MIDI pitch 108, fundamental frequency 4,168 Hz), played on a Roland RD-250s digital piano.[5] The sequences were generated via a musical instrument digital interface (MIDI) under control of a MAX patcher running on a Macintosh Quadra 660 AV computer.[6] Each sequence contained four IOIs whose durations were equal but different from the baseline duration and which were separated by exactly nine baseline IOIs. These changed IOIs will be referred to as "targets," and the advanced or delayed tone onset marking their end will be called the target position (T). The reason for presenting multiple targets on each trial was not only economy but also the consideration that, if compensation does not occur for early targets, the SE would cumulate in the course of the sequence and thereby perhaps trigger compensation for later targets. The regular spacing of the targets facilitated data analysis but was not believed to affect motor compensation, since all changes were subliminal and their locations were unknown to the participants. There were eight target IOI durations, resulting from four increment sizes (Δt = 10, 8, 6, and 4 ms) and four decrement sizes (Δt = −10, −8, −6, and −4 ms), representing changes of 2%, 1.6%, 1.2%, and 0.8%, respectively. Given a typical interval discrimination threshold of about 4%, these changes were clearly subliminal, so that all stimulus sequences sounded evenly timed to the participants. For each of the eight target durations, there were 10 sequences (trials) in which the first target was the 6th, 7th,..., 15th IOI. Thus, there were 80 trials altogether. They were arranged into eight blocks of 10 and randomly ordered within blocks, except that IOI increments and decrements were not mixed, but presented in alternate blocks.

Procedure. Participants sat in front of a computer monitor which displayed the current trial number, listened to the stimuli over Sennheiser HD540 II earphones, and responded on a Fatar Studio 37 MIDI controller (a silent three-octave keyboard) by depressing one white key in synchrony with the pacing tones. Participants were instructed to hold the MIDI controller on their lap, to keep their index finger in contact with the response key, to release the key fully before pressing it again, to avoid fatigue by stiffening finger and wrist and moving the forearm from the elbow joint (a strategy shown by Wing, 1977b, to reduce response variability), to relax their arm between trials, to start tapping with the second tone in each sequence, and to keep in synchrony with the tones at all times. The response key moved about 10 mm from its resting position to the (cushioned) bottom position, but the electronic contact occurred before the lowest position was reached. Assuming a low key velocity of 0.5 to 1 m/s (see Palmer & Brown, 1991), the early contact increased the average asynchrony (i.e., made it more negative) by up to 10 ms. In contrast to most other synchronization studies in the literature, the response key did not make any audible sound, so that participants had to gauge their SEs cross-modally. The times of the key presses relative to the onset of a sequence were registered by the MAX patcher via MIDI. (See Collyer, Boatright-Horowitz, & Hooper, 1997, for a description of a similar set-up.)

[5] The nominal keypress duration (20 ms) was irrelevant because the digital piano simulated the fact that the highest piano strings do not have dampers. The tone onset included the contact noise of a wooden piano key with its key bed. The amplitude reached its peak in about 5 ms and decayed thereafter, first rapidly and then more slowly over several hundreds of ms.

[6] A MAX patcher 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, so that the real-time baseline interval was 488 ms, not 500 ms. 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 MAX, and the constant scaling factor is ignored. Apart from this factor, MAX was highly accurate (within 1 ms) in timing sequences and registering key presses, as confirmed by acoustic measurements.

The experimenter initiated each block of ten trials and saved the data at its end. Short breaks occurred between successive blocks, and a longer break after the fourth block. At the beginning, three practice trials were given. To increase the participants' motivation to be accurate, they were informed in advance about the purpose of the experiment and about the presence of subliminal timing perturbations. This knowledge was not expected to affect their general response strategy, which was simply to stay in synchrony with the seemingly isochronous stimulus sequences.

Analysis. Each participant's recorded MIDI data were imported into a spreadsheet program and sorted according to target duration and location. Asynchronies were computed by subtracting the nominal tone onset times from the registered key contact times. Thus, asynchronies were negative when the tap preceded the tone (as is usually the case in synchronization tasks; see, e.g., Aschersleben & Prinz, 1995) and positive if the tap followed the tone. Occasional errors (such as missing taps) were corrected by realigning the data, leaving missing entries blank. For each target duration, there were ten trials, each of which contained four targets ten positions apart. From each of these series of asynchronies, four episodes of ten positions each were extracted, with each episode comprising three positions preceding a target position (T), T itself, and six positions following T. Asynchronies preceding the first episode and following the fourth episode were disregarded.

Results and discussion

To begin with, a rough index of the extent to which motor compensation occurred in a trial was obtained by computing the difference between the average asynchronies near the beginning and near the end of the stimulus sequences. A change of Δt at point T necessarily changes the asynchrony at that point by $-\Delta t$, on the average. If none of the four changes within a trial is compensated for, then the average final asynchrony should differ from the average initial asynchrony by the cumulative effect of the changes, which is $-4\Delta t$. If there is complete compensation, however, then the average initial and final asynchronies should not differ, unless there is systematic drift of some sort.

Figure 1 shows the predicted cumulative changes in asynchrony (*open circles*) and the actual average asynchrony differences (*filled circles*) between two selected positions: the one immediately preceding the first target ($T_1 - 1$) and the sixth position following the fourth target ($T_4 + 6$). The double standard error bars represent 95% confidence intervals based on the variability among participants. It is evident that the obtained differences were significantly different from the predicted values and not significantly different from zero, except in one case ($\Delta t = 4$ ms) where the difference, however, was not in the predicted direction. This preliminary view of the data suggests that complete compensation occurred for all magnitudes of Δt. The data also indicate that there was no significant drift in average asynchrony in the course of the stimulus sequences.

The average "compensation functions" (relative asynchrony as a function of position near a target) are shown in Figs. 2 and 3 for positive and negative values

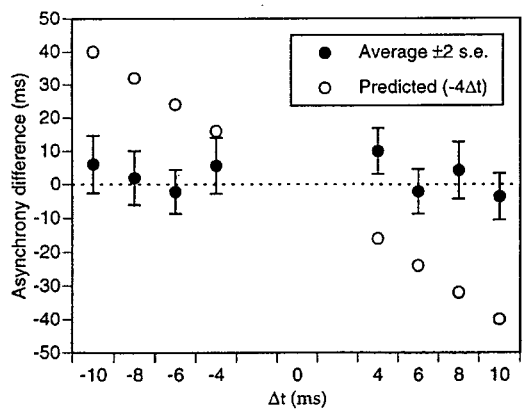

Fig. 1 The difference between the average asynchronies in positions $T_4 + 6$ and $T_1 - 1$ (T = target) as a function of Δt, with *double standard error bars* (~95% confidence intervals). Predicted differences, assuming no compensation at all, are shown as *open circles*

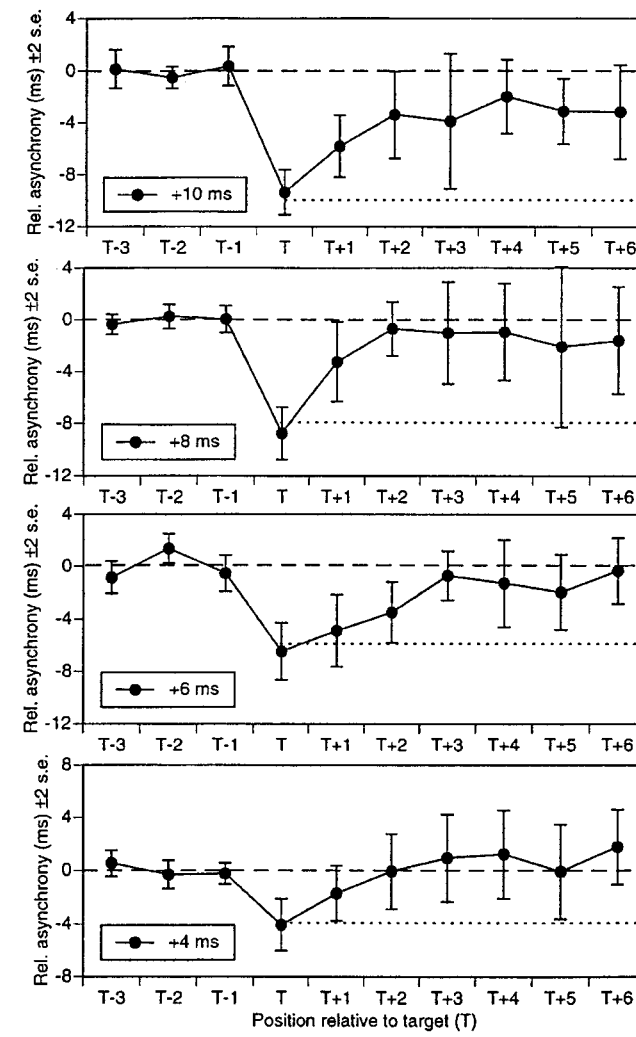

Fig. 2 Average compensation functions (relative asynchrony as a function of position near a target T) for four increment sizes, with *double standard error bars. Dashed lines* indicate the average asynchrony preceding a target (set to zero). *Dotted lines* indicate the expected relative asynchrony following a target in the absence of any compensation

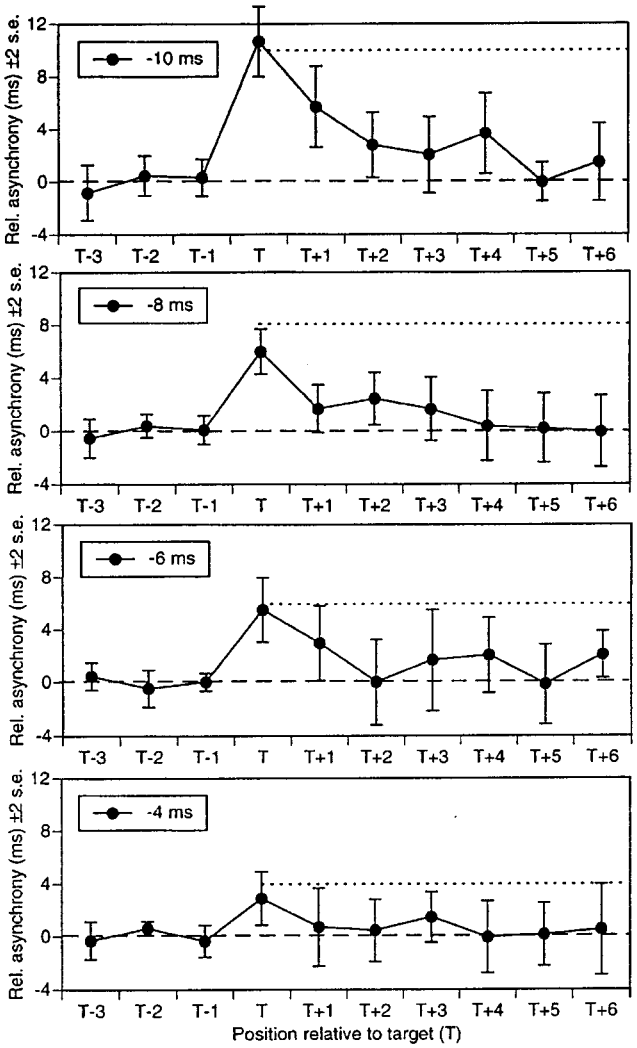

Fig. 3 Average compensation functions for four decrement sizes (analogous to Fig. 2)

of Δt, respectively. Each function is based on a total of $8 \times 40 = 320$ episodes. The double standard-error bars are based on the variability among participants. To exclude irrelevant variation due to individual differences in the average magnitude of the anticipation tendency (see below), each participant's compensation functions were first relativized by computing the average asynchrony of the three positions preceding a target and subtracting this value from all asynchronies in an episode. (The small standard errors in the three initial positions are thus an artifact.) The resulting relative asynchronies have a zero pre-target baseline, indicated by the dashed horizontal lines in the figures. The dotted horizontal lines in the figures represent the relative asynchrony expected in the target position (i.e., $-\Delta t$) and in the following positions, if there was no compensation at all. Compensation is shown by a return of the relative asynchronies to the zero line in the positions following a target. Such a return can be seen in all Δt conditions, generally within two or three taps. From position T + 2 or T + 3 on, the average relative asynchronies were generally not significantly different from zero, but they were significantly different from the expected values represented by the dotted lines. The only exceptions occurred, surprisingly, in the conditions with the largest changes (+10 and −10 ms), where compensation seemed not quite complete, and significant differences from zero occurred four or five taps after a target. Evidence for compensation was obtained even in the conditions with the smallest Δt (+4 and −4 ms): The relative asynchronies were significantly different from zero in the target position only, and significantly different from the predicted value in all following positions. If anything, therefore, compensation was faster and more complete for small than for large perturbations.

To verify that compensation occurred regardless of the location of the target in the sequence, separate two-way repeated-measures ANOVAs were conducted on the absolute asynchronies for the different sizes of Δt. The fixed factors were position (10 levels, from T − 3 to T + 6) and serial order (4 levels, from first to fourth in the sequence); the random factor was participants. If compensation was less effective early in the sequence than later on, a significant position by order interaction should emerge as well as a main effect of order, due to the cumulative phase error; otherwise, there should only be a main effect of position. The position main effect was indeed significant ($p < .02$ or less) in all conditions except for 4-ms decrements, whereas the position by order interaction was nonsignificant in all conditions. The order main effect was significant for 10-ms decrements only, $F(3,21) = 7.47$, $p < .002$, indicating persistent undercompensation (cf. Fig. 3, top panel) and hence increasingly less negative asynchronies in the course of a sequence; a tendency in the opposite direction for 10-ms increments (also indicating undercompensation; cf. Fig. 2, top panel) fell short of significance. These results, as well as informal inspection of the data, suggest that compensation occurred similarly for both early and late targets in a sequence.

The average data shown in Figs. 1–3 are fairly representative of the results for individual participants. Nevertheless, some additional comments on individual differences are in order. These concern (a) the magnitude and variability of the average phase error and (b) the relative rapidity of the compensation.

As expected, all participants showed negative asynchronies (the well-known anticipation tendency) throughout, except at the very beginning of the stimulus sequences: Four of the eight participants showed a much less negative or even positive average asynchrony for their first tap (to the second tone in the sequence), and three others showed a small tendency in the same direction. The characteristic negative asynchrony was usually reached by the third tap, as observed long ago by Fraisse (1966) and more recently by Semjen et al. (1998). The author, who happened to be the oldest participant by far, was an exception; it took him about eight taps to

"tune in" to the stimulus sequence. Average individual anticipation errors ranged from approximately −20 to −60 ms. Some participants exhibited systematic trends or drifts in the average anticipation error in the course of a trial: Several showed a gradual increase (reduced negativity) in the course of the first half of the sequence, and at least one (a graduate student of music theory) showed periodic minima, suggesting a cognitive organization into groups of eight taps. However, removal of these trends from the data left the compensation functions virtually unchanged, which is not surprising in view of the balanced distribution of target positions.

Individual variability of asynchronies tended to be large for the initial tap (in some participants) and fairly stable from then on. Individual variability was assessed across rather than within episodes and thus included between-trial variation in the average anticipation tendency as well as between-episode variability within trials. Nevertheless, six of the eight participants had average standard deviations between 15 and 20 ms (3–4%), which represents good tapping accuracy (see, e.g., Peters, 1989). One participant had a value of 24 ms, and another (surprisingly, the only aspiring professional musician in the group) had the rather large value of 32 ms. There was no clear relationship between the size of the individual anticipation tendency and variability. A tendency was noted, however, for variability to increase slightly during the compensation phase following a target, with a maximum in positions T + 2 and T + 3. This tendency was statistically significant, $F(9,63) = 3.6$, $p < .002$, in a two-way repeated-measures ANOVA on the average standard deviations, with direction of change (increments vs. decrements) and position (10 levels, from T − 3 to T + 6) as fixed factors.

Some individual differences in the speed of compensation were noted. In particular, the author showed slower motor adaptation than other participants, as had also been noted in the earlier study of Repp (1999a). It took him about four taps to compensate, whereas others compensated within one or two taps. This could be an age-related difference. A more detailed discussion of individual differences among the same participants will be provided in connection with Exp. 3, which yielded more stable data.

The results of Exp. 1 show that perturbations well below the interval discrimination threshold are compensated for quickly and effectively, on the average. Even though detection thresholds were not determined in this experiment, substantial psychophysical research and participants' introspections safeguard the assumption that the stimulus perturbations were indeed subliminal. Still, a sceptic might wonder whether tapping in synchrony with an auditory sequence might lower the explicit detection threshold for timing perturbations. This seems unlikely, but it is true that the interval discrimination threshold has not been determined previously in the context of a synchronization task. However, Exp. 5, reported below, addressed this issue and confirmed that the detection threshold was in the expected region (4–5%).

To the extent that timekeeper period correction was involved in the observed motor compensation, the results of Exp. 1 refute TH2, the period correction threshold hypothesis. However, there is little reason to assume that period correction did occur. Since each timing perturbation affected only a single stimulus period but created a constant phase shift, it seems likely that the compensation mechanism was one of pure phase error correction, without any period adjustment. Of course, it is necessary to adjust the *response* IOIs in order to correct the phase error. However, according to the two-level model of Vorberg and Wing (1996), this can be done locally, without changing the period of the mental timekeeper that drives the motor response. Their model states that

$$A_{i+1} = (1 - a)A_i + C_i + M_{i+1} - M_i - S_i$$

where A_i and A_{i+1} are the asynchronies on successive taps, a is a correction parameter, C_i is an interval generated by an internal timekeeper, M_i and M_{i+1} are random motor delays of successive responses with equal means and variances, and S_i is an IOI in the stimulus sequence (after Vorberg & Wing, 1996, eq. 20). Averaging over many trials leads to expected values (E) for $M_{i+1} - M_i$ and $C_i - S_i$ that are close to zero, except in the target position T, where $C_i - S_i = -\Delta t$, with $\Delta t = S_i - S_{i-1}$. This leaves $E(A_{i+1}) = (1 - a)E(A_i)$, where $E(A_i) = -\Delta t$ in position T and zero in immediately preceding positions, given that the asynchronies are expressed relative to the average pre-target asynchrony, which is taken to represent the PSS. A value of $a = 1$ then indicates immediate and full compensation on the following tap, $a = 0$ no compensation at all, and $0 < a < 1$ gradual compensation in the course of several taps. According to the recursive formula, this gradual compensation should follow an exponential function. The correction parameter a is assumed to be independent of the magnitude of the asynchrony to be compensated for, so that the compensation functions in Figs. 2 and 3 should all represent the same exponential function from position T on.

The compensation functions for the individual Δt conditions in Figs. 2 and 3, although somewhat variable, do not seem inconsistent with this model. In an attempt to further reduce the variability, the eight compensation functions from position T on were transformed so that the expected asynchrony in position T was 1, and the expected asymptote was zero. (This entailed a mirror reversal of the compensation functions for IOI increments.) The normalized functions were then averaged, and the standard errors of the average values were calculated across the eight Δt conditions. The resulting grand average compensation function, with double standard-error bars, is shown in Fig. 4. The dashed curve shows an exponential function with an initial value

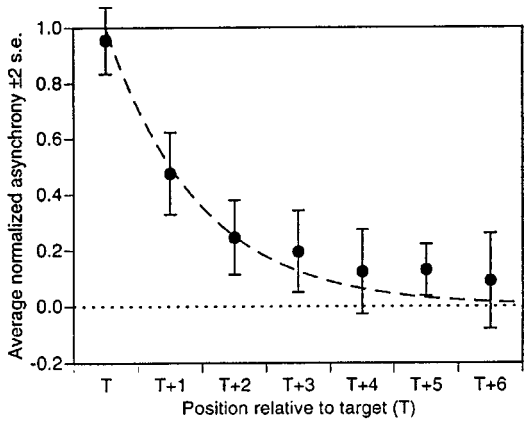

Fig. 4 Grand average normalized compensation function for all conditions of Exp. 1, with *double standard error bars*. The *dashed curve* is an exponential compensation function with a correction parameter of 0.5

of 1 and $a = 0.5$.[7] This function fits the initial three data points very well, but reaches asymptote more quickly than the actual data, due to a slight undercompensation (which remains unexplained for the time being). However, since the function generally falls within the 95% confidence intervals of the data points, the phase error correction model of Vorberg and Wing (1996) seems adequate to explain the data.

If the error correction process is based solely on the phase error, then the data of Exp. 1 are irrelevant to TH2. We may ask now whether they have anything to say about TH1, the hypothesis that a temporal order threshold limits phase error correction.

The phase error is extremely variable from tap to tap, so that data from single trials are almost impossible to interpret. Given typical standard deviations of about 20 ms across episodes, the asynchrony in any particular position will sometimes (about one third of the time) deviate from the mean asynchrony (assumed to represent the PSS) by more than about 20 ms, the temporal-order threshold established by Hirsh & Sherrick (1961). A shift in stimulus phase by Δt will lead to a shift in the mean of the phase error distribution by $-\Delta t$, thus increasing the probability of supra-threshold deviations in one direction and decreasing that of deviations in the other direction. Could it be that the compensation functions for subliminal timing perturbations derive solely from compensation for supraliminal phase errors whose probability of occurrence is changed by the stimulus perturbation?

Intuitively, this seems unlikely, because compensation was relatively fast – within one or two taps for most participants. Given a probability of supra-threshold phase errors of about 1/3, even perfect compensation for such errors ($a = 1$) could not easily lead to complete average compensation within one or two taps. There is also additional relevant information hidden in the data of Exp. 1. Specifically, we may ask whether compensation occurred in those episodes in which the phase error in position T was actually smaller than 20 ms. To address this question, each participant's data for all eight Δt conditions combined ($8 \times 4 \times 10 = 320$ episodes) were sorted into 10-ms bins according to the magnitude of the absolute asynchrony in position T. The episodes in each bin were then averaged. For each participant, a center bin in the middle of his or her range (presumably the one closest to the PSS) was then selected, the other bins were re-labeled relative to the center bin, and the data were aligned according to these labels and averaged across participants. This analysis was based on the assumption that phase error correction operates independently of whether a particular asynchrony arises from a stimulus perturbation or from response variability: The perturbations merely increased the range of asynchronies observed in position T.

The results are shown in Fig. 5a, with error bars omitted for clarity. The graph suggests that, with the exception of the center bin, the phase error at position T in each bin returned to its pre-target baseline level within two or three taps, even for asynchronies that were within 20 ms of the PSS, that is below the usually quoted temporal order threshold. In particular, there was a change in the average phase error between positions T and T + 1, where a threshold should have prevented any adjustment from occurring. (From position T + 1 on, response variability will again generate some supra-threshold phase errors.) This change was significant in all bins, including those nearest the center bin (C): For asynchronies around C – 10 ms, it was 3 ms, $F(1,7) = 22.0$, $p < .002$, and for asynchronies around C + 10 ms, it was −5.3 ms, $F(1,7) = 13.6$, $p < .008$. These results seem contrary to TH1 and consistent with the linear phase error correction model of Vorberg and Wing (1996), which does not include a threshold for phase error correction. The strong covariation of the pre-target baseline with the selected magnitude of the asynchrony in position T is a reflection of the covariance structure of the time series, which may itself be in part a consequence of the continuous phase error correction process. Statistical modelling of the data would be required to illuminate this point further, but this is beyond the scope of this study.

One possible objection to the foregoing analysis is that the PSS may be unstable and subject to systematic drift between trials and episodes. In fact, such drift may be partially responsible for the positive correlations among successive asynchronies. This point was addressed by sorting the data according to the *relative* asynchrony in position T. The average asynchrony of the three pre-target positions was subtracted from the asynchronies in each individual episode, and the episodes were then sorted into 10-ms bins. The data, averaged across participants, are shown in Fig. 5b. Here, the pre-target baseline is zero by definition for all

[7] Pressing (1998), using statistical modelling, estimated an a value of 0.54 for a single expert tapping to an isochronous sequence with IOIs of 500 ms

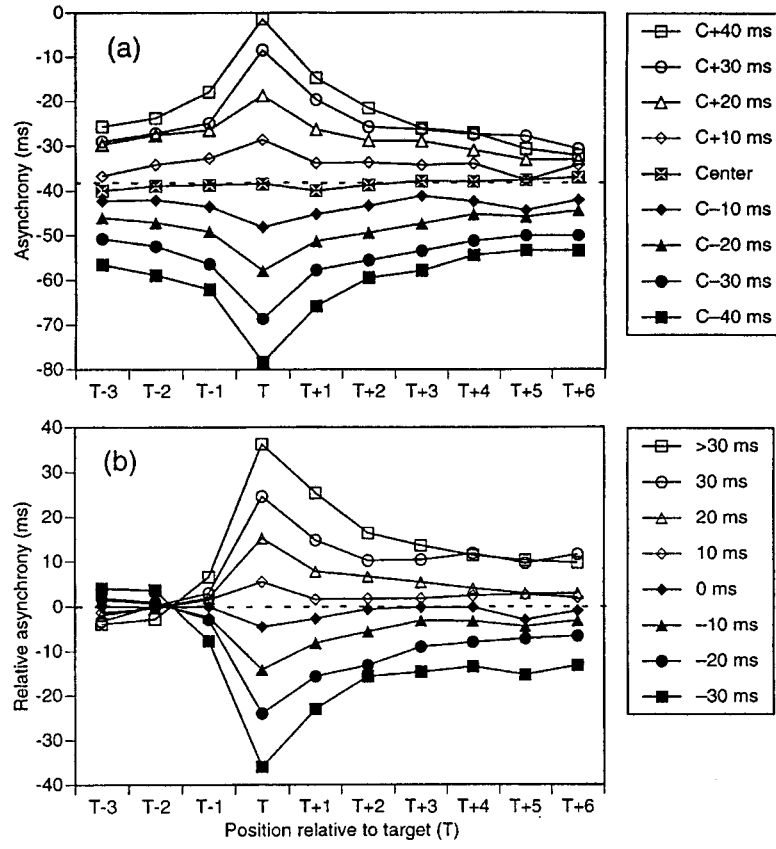

Fig. 5 **a** Average compensation functions for selected magnitudes of the absolute asynchrony in position T, grouped into 10-ms bins relative to a bin in the center of the range. The legend refers to the centers of the bins. **b** Average compensation functions for selected magnitudes of the relative asynchrony in position T, grouped into 10-ms bins whose upper limits are shown in the legend. The outer bins include ranges wider than 10 ms

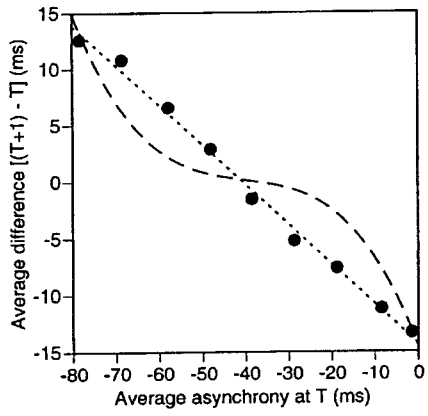

Fig. 6 The difference between the average asynchronies in positions T + 1 and T as a function of the average asynchrony in position T for 10-ms bins (data from Fig. 5a). The *dotted line* is the best-fitting straight line. The *dashed line* indicates schematically the prediction of a threshold model

compensation functions. Again, however, all functions converge, including those with relative phase errors of less than 20 ms, and particularly between position T and T + 1. However, they do not converge onto zero; rather, their asymptotes seem to be at about half the relative asynchrony in position T. This must be a reflection of the same statistical dependencies among successive asynchronies that were evident in Fig. 5a. The change between positions T and T + 1 was again significant in all bins, including those containing the smallest asynchronies: For asynchronies between −10 and 0 ms, it was 1.8 ms, $F(1,7) = 5.8$, $p < .05$, and for asynchronies between 0 and 10 ms, it was −4 ms, $F(1,7) = 10.0$, $p < .02$.

To reinforce the point of the foregoing analyses, Fig. 6 replots a subset of the data from Fig. 5a. The difference between the average asynchronies at points T + 1 and T is shown as a function of the average asynchrony at point T for all 10-ms bins. These data points are fitted well by a straight line with a slope of −0.35, which corresponds to an average phase error correction parameter a of 0.35. (A very similar relationship is obtained for the relative asynchrony data of Fig. 5b.) The dashed line in the figure indicates schematically the relationship that would be predicted by a threshold model, which is clearly inconsistent with the data.[8]

It seems that TH1 can be rejected on the basis of these findings. Nevertheless, there remains a question of whether the temporal order threshold in this cross-

[8] This prediction was confirmed by a binned analysis of computer-generated data simulating first-order phase error correction with and without a threshold, which were kindly provided by Jeff Pressing. For a similar type of analysis, see Pressing (1998). The estimate of a arising from Fig. 6 is lower than that suggested by Fig. 4, for reasons that are not quite clear.

modal kinesthetic-auditory paradigm is really within 20 ms of the PSS. The hypothesis that phase error correction can (indeed, typically does) occur without conscious awareness has considerable intuitive appeal and seems to agree with introspection. However, the temporal order threshold has not previously been determined in the context of a synchronization task. Accordingly, Exp. 2 was conducted.

Experiment 2

The cross-modal auditory-tactile temporal order judgment experiment of Hirsh and Sherrick (1961) differs in several respects from the synchronization paradigm. First, the tactile stimulus was received passively from a vibrator, not generated actively through movement and kinesthetic feedback. Second, each trial consisted of a single stimulus pair, whereas in a synchronization task, events follow each other rapidly. Third, the PSS was close to zero (there was a small constant error in favor of the tactile stimulus leading the auditory one), whereas in synchronization tasks the PSS is typically at a negative asynchrony. Actually, it has only been assumed, not demonstrated directly, that the PSS coincides with the average asynchrony in synchronization. Finally, the participants in the Hirsh and Sherrick study had been trained to perform optimally in the task, whereas the participants in synchronization experiments are not usually trained in making temporal order judgments.

While there seems to be no previous study that requested participants to judge the temporal order of events in a synchronization paradigm, some observations in the literature suggest that the auditory-kinesthetic temporal order threshold may be a good deal higher than ±20 ms relative to the PSS. Wing (1977a) had participants tap freely at a regular rate, but provided auditory feedback about the taps at delays of either 15 or 25 ms and then perturbed the auditory feedback by delaying the sound for a single tap by as much as an additional 50 ms. Wing claims that these delays were not noticed by the participants. Aschersleben and Prinz (1997) likewise varied auditory feedback delay, but between trials. Their delays varied from 0 to 70 ms, and post-experimental interviews indicated that none of the participants had noticed this variation. These authors also mention pilot observations which suggested that delays of up to 100 ms were not noticed, provided the participants were not alerted to their presence.

These results are only suggestive, of course, and what is needed is an experiment in which participants directly judge their own phase errors in a synchronization task. This was the purpose of Exp. 2. Of course, it is out of the question to ask for continuous judgments at a tapping rate of 2/s, and therefore only a single judgment per sequence was obtained, namely for the final tap/tone. Four response choices were offered, following Allan (1975b), who has shown that temporal order judgments with two degrees of confidence yield results very similar to those from separate successiveness and temporal order judgments (Allan, 1975a).

Method

Participants. Six of the eight participants in Exp. 1 returned for Exp. 2 almost one year later, after participating in Exps. 3–5. They included the author (B.R.) and his research assistant (P.B.), who were the most experienced tappers, having gone through many additional pilot runs.

Stimuli. Thirty short sequences were created, using the same tones and equipment as in Exp. 1, except that the final tone was lowered by 3 semitones (to A_7, MIDI pitch 105). This was done to signal the end of a sequence and to prevent the occurrence of an additional tap. The baseline IOI was 500 ms. The sequence length varied from 6 to 15 tones in steps of 1. The final IOI in each of these ten sequences was 490, 500, or 510 ms (i.e., $\Delta t = -10$ ms, 0 ms, and $+10$ ms). The perturbations of the final IOI were applied to increase the range of asynchronies in the final position. Being well below the interval discrimination threshold, they were not expected to influence the participants' judgments of the phase errors. Altogether, then, there were 30 sequences or trials.

Procedure. Participants received one practice block of 30 trials and ten test blocks in which the same 30 trials occurred in different random orders. They held the Fatar Studio 37 MIDI Controller on their lap and tapped on a white key in synchrony with the tones, starting with the second tone in a sequence. After each trial, they clicked with a mouse on one of four response buttons displayed on a computer monitor. Above the two larger buttons it said, "My tap did NOT coincide with the last tone. I noticed that...", and next to the buttons it said "...my tap was TOO EARLY" and "...my tap was TOO LATE", respectively. Further down on the screen, above two smaller buttons it said, "My tap seemed to coincide with the last tone. Nevertheless, I am guessing that...", and next to the buttons it said "...my tap was EARLY" and "...my tap was LATE", respectively. The participant's response with the mouse triggered the next trial, which started 4 s later. The experiment was controlled by a MAX patcher.

Results and discussion

The final asynchronies of each participant's 300 trials were sorted and grouped into 5-ms bins, such that each bin contained at least ten observations. The extreme bins contained a wider range of values. The percentages of each response category were then calculated for each bin.[9] The individual results are displayed in Fig. 7 in terms of the percentage of "tap was early" responses (*filled circles*), which includes both confident responses and guesses. A linear function (*dotted line*) has been fitted to these data. For two participants (P.B. and T.B.),

[9] To make sure that the perturbations in the final IOI had not influenced the participants' judgments, the data were also sorted separately for each Δt into 10-ms bins. Retaining only those bins containing at least ten observations for each Δt, the percentage of "tap was early" responses was calculated for each Δt. These percentages were then averaged across bins (two bins for five participants, three bins for one) and submitted to a one-way repeated-measures ANOVA. The average response percentages for $\Delta t = -10$ ms, 0 ms, $+10$ ms were 53, 45, and 53, respectively, and they did not differ significantly, $F(2,10) = 1.87$, $p < .21$.

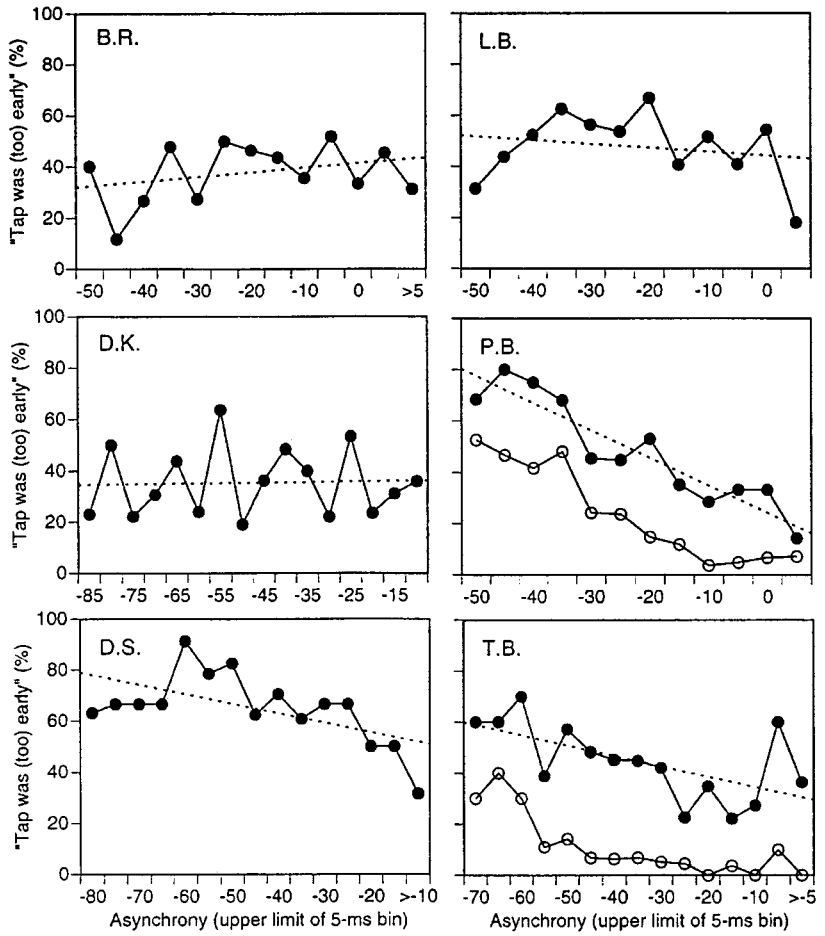

Fig. 7 Percentage of "tap was (too) early" responses (*filled circles*) as a function of asynchrony magnitude, for six individual participants in Exp. 2. *open circles* for two participants represent confident responses only. *Dotted lines* are linear regression fits

the percentage of confident "tap was too early" responses is displayed separately (*open circles*).

The only participant who was reasonably successful in this task was P.B., though even he reached only about 80% correct at the extremes of his (relatively narrow) range of asynchronies. His success was entirely due to his confident responses; his guesses (the difference between the two functions displayed) were basically at chance. His data are consistent with temporal order thresholds (25% or 75% correct) of about ±20 ms from the PSS (50% correct), as reported by Hirsh and Sherrick (1961).

Three participants (D.S., L.B., and T.B.) showed some marginal ability to judge the direction of the asynchronies. D.S. and L.B. hardly ever used the confident response categories (not shown), and D.S. moreover had a bias to judge his taps as being early. Their response percentages increased as the asynchrony became more negative, but then paradoxically dropped for long negative asynchronies. T.B. showed a paradoxical peak at the other end of the asynchrony continuum. He sometimes gave confident responses at the extremes of the asynchrony range, and they were usually correct, accounting largely for the overall trend in his data.

Two of the participants (B.R. and D.K.) were totally at sea. For B.R. (the author), tap and tone always seemed to coincide, so that he never used the confident response categories. D.K. used the confident response categories quite frequently but randomly; therefore, they are not shown in the graph. Both these participants also showed a bias to judge their taps as being late, regardless of the actual asynchrony.

Thus, there were large individual differences. All six participants, however, showed compensation for small phase errors and subliminal timing perturbations in Exp. 1. The results of Exp. 2 thus confirm what already seemed obvious from introspection, namely that asynchronies are processed subconsciously and automatically, without the limitation of a perceptual threshold. Therefore, TH1 can be rejected. Although Exp. 2 does not rule out the possibility that phase error correction is limited by an underlying temporal order threshold of about ±20 ms that, in this instance, does not correspond to the actual threshold of most participants (though it would perhaps reveal itself after extensive training), the binned analysis of the Exp. 1 data argues against this hypothesis. Mates's (1994b) study notwithstanding, there is also evidence from other research that phase error correction models without any threshold assumption fit synchronization data well (Pressing, 1998, 1999).

Preamble to Experiments 3–5

The original purpose of Exps. 3–5 was to investigate whether factors that are known to affect interval discrimination also affect the average time course of compensation for subliminal timing perturbations of the pulse type. These experiments were conducted before the distinction between TH1 and TH2 had become clear in the author's mind, and thus they had been conceived with the possibility in mind that compensation for pulse changes is based on subliminal perceptual information about changes in stimulus interval duration. However, it seems highly likely now that this premise was incorrect and that compensation for pulse changes is based on perception of the SE only.

There is no direct evidence that the factors manipulated in Exps. 3–5 affect the temporal order threshold. Nevertheless, it could be argued that, because interval duration is the difference between two successive tone onset times, factors that affect interval perception should also affect the perception of one or both tone onsets that delimit the interval. If the effect is one of lowered sensitivity to changes in interval duration (as in Exps. 4 and 5), then there should also be greater uncertainty about tone onset times and hence about the SE. If the effect is a bias, so that some intervals seem longer or shorter than they really are (as in Exps. 3 and 5), then one of their delimiting tone onsets should appear to be shifted in time, with consequences for phase error correction. Alternatively, factors that affect interval discrimination and perceived interval duration may not have any effect on perceived tone onset times, and hence may also leave the perceived SE and phase error correction unaffected. This latter result would suggest that contextual effects on perceived interval duration are specific to interval perception and judgment. Experiments 3–5 may now be seen as addressing this issue. In addition, each experiment also had some secondary purposes, as described below.

Experiment 3

In the Introduction, an earlier experiment (Repp, 1999a: Exp. 2) was mentioned in which participants had tapped in synchrony with music containing pulse-type IOI increments of 20 or 40 ms. The explicit detectability of such increments varies greatly with position in the musical structure (Repp, 1992, 1998a, 1998b, 1999a). In the synchronization task, however, motor compensation for the timing perturbations was equally rapid and complete in high- and low-detectability positions. This finding suggested that automatic error correction derives temporal information from a processing stage that precedes the influence of muscial structure on timing perception. The aim of Exp. 3 was to replicate this result with subliminal timing perturbations and simultaneously to demonstrate that effective compensation for subliminal changes occurs not only in simple tonal sequences (Exp. 1) but also in the context of complex music.

Another reason for conducting this experiment was that there was a difference between the average compensation functions of the earlier music experiment (Repp, 1999a) and the present Exp. 1: Compensation in music was immediate (within one tap), whereas at least two taps seemed to be needed, on the average, in Exp. 1. The faster compensation in the earlier study could have been due to either the fact that the timing perturbations were often detected explicitly or that they were embedded in music rather than in a simple sequence of tones. By using subliminal timing changes in music, Exp. 3 tried to resolve this issue.

A further reason for conducting Exp. 3 was to obtain more stable individual data. In Exp. 1 there had been only 40 episodes per Δt condition and participant, whereas in Exp. 3 there were 180, at the cost of using only two Δt values. This was expected to lead to less variable average compensation functions that would permit stronger conclusions about their temporal shape. Only IOI increments were used in Exp. 3 because, unlike IOI decrements, they have an important expressive function in music: the lingering that marks important events and structural boundaries.

Experiment 3 was also expected to replicate a finding obtained previously with the same musical excerpt (Repp, 1999a,b) and with two longer pieces (Repp, 1999c), namely that the asynchronies in synchronization with perfectly metronomic music (i.e., with timing perturbations either absent or excluded from analysis) exhibit systematic variations in the course of the music. These variations seem to be related to the melodic-rhythmic grouping structure and to the timing pattern in expressive music performance.

Method

Participants. The eight participants were the same as in Exp. 1.

Stimuli. The musical excerpt was the beginning of Chopin's *Etude in E major*, Op. 10, No. 3, terminated with a sustained chord (a modification of the original music). A computer-generated score is shown on top of Fig. 8. The initial eighth-note upbeat was followed by continuous motion in sixteenth-notes; that is, there were note onsets at regular intervals, eight per bar, even though the soprano melody was segmented into rhythmic groups, each ending with a long note. The music was synthesized under computer (MIDI) control on a Roland RD-250s digital piano, with a baseline sixteenth-note IOI duration of 500 ms. The MIDI instructions were created in text format in a spreadsheet program and were executed by a MAX patcher. The MIDI "note on" and "note off" commands were in accord with the nominal note values in the score, and the sustaining pedal was not used. The relative intensities (MIDI velocities) of the individual tones represented the average values of 27 performances by 9 advanced student pianists (data collected by Repp, 1998a). They appropriately emphasized the melody over the accompanying voices and gave the melody a dynamic arch that roughly followed the pitch contour.

The music contained 36 sixteenth-note IOIs or positions. Each trial contained four pulse-type IOI increments of the same size, spaced nine positions apart. The first increment occurred in

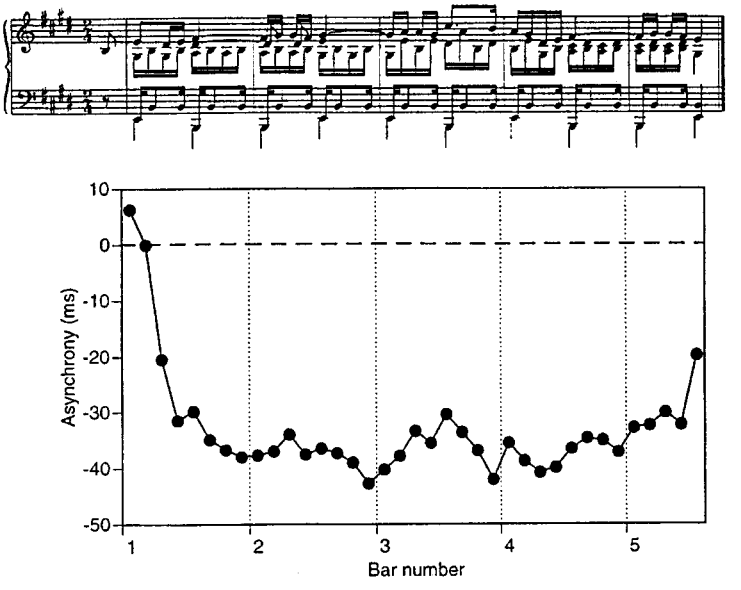

Fig. 8 The beginning of Chopin's *Etude in E major*, Op. 10, No. 3 and the average asynchrony profile for the strictly metronomic portions of the music

positions 1 through 9; thus, the resulting stimuli ranged from one containing increments in positions 1, 10, 19, and 28 to one containing increments in positions 9, 18, 27, and 36. In the course of these nine stimuli, each of the 36 IOIs was incremented once. A tenth stimulus without any IOI increments was included (unnecessarily, as it turned out). The two Δt sizes were 6 and 10 ms. Five blocks of ten trials each were presented, with Δt constant within blocks and alternating between blocks. The trials were ordered randomly within each block.

Procedure. The procedure and equipment were the same as in Exp. 1. Participants did a few practice trials to familiarize themselves with the music. They were instructed to start tapping with the second event onset (the first downbeat) and with every sixteenth-note from then on (i.e., 37 taps).

Analysis. Individual participants' asynchronies were expressed relative to their average "baseline asynchrony profile," which resulted in a grand average asynchrony near zero. The baseline asynchrony profile was the average asynchrony as a function of position for a completely metronomic stimulus. It was computed initially by averaging across the 10 trials not containing any IOI increments. However, this estimate proved to be too variable, and a procedure used previously by Repp (1999a; Exp. 2) was employed, instead: All asynchronies in positions T, T + 1, and T + 2 were deleted from the trials containing targets, and then the remaining asynchronies were averaged across all 50 trials for a given increment size, including the 5 trials without any targets. After subtracting these baseline asynchronies to obtain relative asynchronies, the data were divided into target episodes spanning nine positions (T − 3 to T + 5) and were averaged over episodes.

Results and discussion

Figure 8 shows the grand average baseline asynchrony profile, averaged across both Δt sizes and all participants. No standard errors are shown, as they would reflect mainly individual differences in the anticipation tendency. It can be seen that the average anticipation tendency was initially absent and emerged only after three or four taps. It was about twice as large as in Repp (1999a), almost certainly due to the use of a different response key.[10] The range of individual differences was similar to that in Exp. 1 (about −20 to −60 ms). The variations in the asynchrony profile seem small, but they were significantly similar to those obtained previously for the same music (Repp, 1999a: Exp. 2), even without the initial three and single final data points, $r(30) = 0.70$, $p < .001$. The variation (with the same data points excluded) was also significant in a one-way repeated-measures ANOVA, $F(32,224) = 2.6$, $p < .001$. This goes to show that the error correction process took place against a background of systematic variations in the phase error induced by the musical structure. There were considerable individual differences in the shape of the baseline asynchrony profile, and the profiles for individual participants were more varied than the average function in Fig. 8.

The average compensation functions for the two increment sizes are shown in Fig. 9. These functions were averaged over all 36 positions in the music (each of 9 trials yielding 4 target episodes), 5 replications, and 8 participants, so that each data point is based on 1,440 observations. As a result, these functions are cleaner in appearance than those of Exp. 1. The double standard error bars represent the variation among participants. In contrast to Exp. 1, there was no indication of under-

[10] Participants in the earlier study had tapped on a computer keyboard. The author ran himself twice on a pilot version of Exp. 1, using first the computer keyboard and then the MIDI controller to respond, and found that his anticipation error increased by a similar amount. The MIDI controller key traveled a greater distance and made a softer, noiseless contact with the key bed. The difference is consistent with one plausible explanation of the anticipation tendency, namely that participants aim for a point beyond the key bottom contact, corresponding to the turning point of a virtual sinusoidal motion path (Vaughan, Rosenbaum, Diedrich, & Moore, 1996; Vaughan, Mattson, & Rosenbaum, 1998).

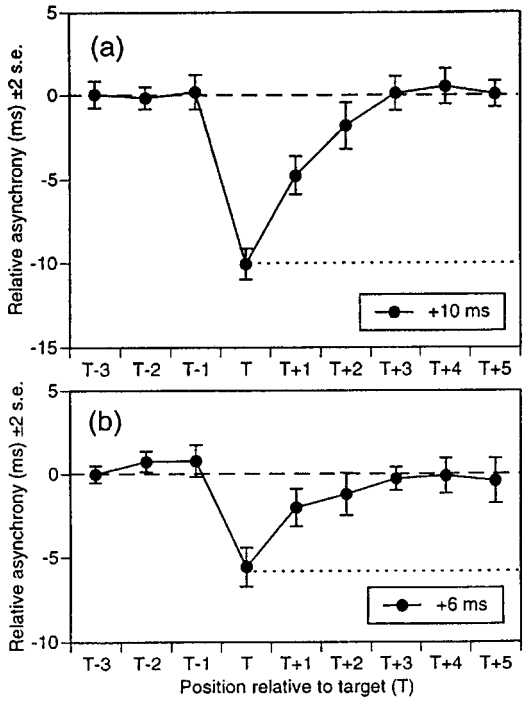

Fig. 9 Average compensation functions for two increment sizes in Exp. 3, with *double standard error bars*

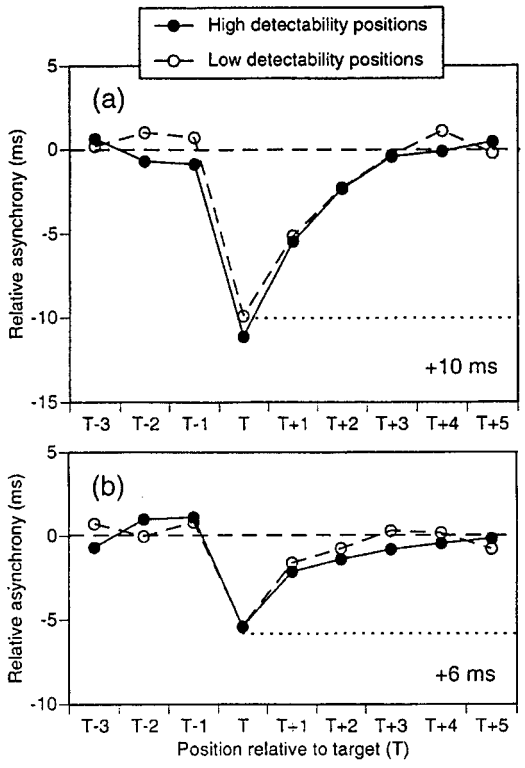

Fig. 10 Average compensation functions for high- and low-detectability positions in the music, for each of two increment sizes in Exp. 3

compensation here. For both 10-ms and 6-ms increments, compensation was complete within three taps, on the average. This was similar to Exp. 1 but slower than the average compensation for larger perturbations in the same music (Repp, 1999a: Exp. 2). This raises the possibility that there is a difference in speed of compensation for sub- and supraliminal (or simply smaller and larger) timing perturbations, which was investigated further in Exp. 5. The curvilinear shape of the 10-ms compensation function is consistent with a simple phase error correction model with a correction parameter of about 0.5; that of the 6-ms compensation function also seems compatible with such a model, in view of the 95% confidence intervals.

Next, the relationship between the effectiveness of compensation and position in the musical structure was examined. Even though the present IOI increments were very small and thus hardly ever detected, the 32 interior positions in the music (the initial 2 and final 2 positions were omitted) were divided into two groups of 16, labelled "high-detectability" (H-D) and "low-detectability" (L-D) according to the detection results of Repp (1999a: Exp. 1). Separate average compensation functions were computed for these two groups. They are shown superimposed in Fig. 10. No statistical analysis is necessary to conclude that compensation in L-D positions was just as effective as in H-D positions, as had been the case in Repp (1999a: Exp. 2) for larger IOI increments that were actually detectable some of the time. This confirms that the automatic error correction process is independent of structural factors that modulate the explicit awareness of timing perturbations in metronomically played music. Yet, the baseline asynchronies (Fig. 8) were modulated by the very same (or similar) structural factors.[11] On the average, the *absolute* asynchronies in L-D positions were 3.3 ms longer (i.e., less negative) than in H-D positions. Thus, the Δt of 6 ms was effectively only 4.35 ms in the former positions, but 7.65 ms in the latter. Nevertheless, compensation was equally effective, which confirms that phase errors of all magnitudes are compensated for, even in synchronization with music.

These *actual* differences in the average absolute asynchronies between L-D and H-D positions, due to response timing, must be distinguished from any *apparent* differences in note onset times, due to perceptual bias. In L-D positions, IOI increments are difficult to detect, which implies that these intervals are perceived as shorter than they really are. Therefore, the tone onsets terminating them may be perceived as occurring too early. When such a tone is then delayed by Δt, the SE should be perceived as smaller than it really is, and undercompensation should be the result. Similarly, in H-D positions, overcompensation should occur. The results do not show this pattern and therefore do not support

[11] A discussion of these structural factors is beyond the scope of this article, especially since there is still considerable uncertainty about the interpretation of this finding. Suffice it to say that the baseline asynchrony profile does not simply reflect the metrical structure of the music.

the hypothesis that the perception of tone onsets and SEs is subject to the bias that musical structure exerts on interval perception. This finding is potentially problematic for a theory that explains interval perception in terms of predictive oscillatory processes (McAuley & Kidd, 1998).

It is important to realize that an average compensation function of roughly exponential shape does not prove that individual compensation functions have the same shape. Therefore, it is instructive to examine the compensation functions for the individual participants, which are shown in Fig. 11. The three positions preceding a target have been excluded here, and error bars are omitted, too, so as not to clutter the figures too much. Individual average standard deviations in this experiment ranged from 17 to 25 ms, and since there were 180 observations per data point, average standard errors ranged from 1.3 to 1.8 ms. Thus, even though some of the average relative asynchronies in position T seem to deviate from the expected values of −6 and −10 ms, they are generally within the 95% confident intervals. The figure reveals considerable individual differences in speed of compensation: Complete compensation occurred within one tap (T.B.), two taps (A.S., D.S., L.B., L.F.), three taps (DK., P.B.), and four taps (B.R.). Again, it is noteworthy that B.R. was the oldest participant by far, and P.B. the second-oldest. The other thing to note is the shape of the individual functions. The slower compensation functions provide more information here because they comprise more data points. Clearly, the pre-asymptotic portions of the individual functions of B.R., D.K., P.B., L.B., and L.F. are better described as linear than as exponential functions. Only the 3-point functions of A.S. and D.S. for 10-ms increments suggest some curvilinearity. The curvilinear appearance of the average functions in Fig. 9 thus seems to be largely an artifact of averaging over participants. This suggests that the model of Vorberg and Wing (1996)

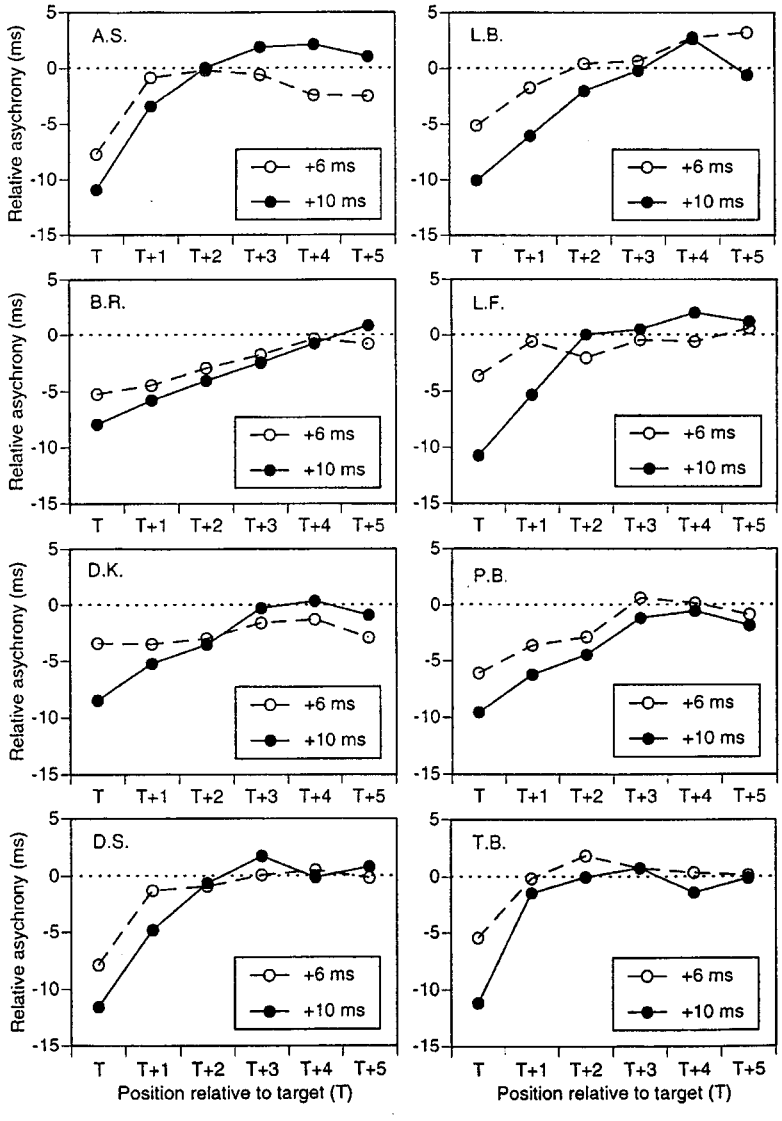

Fig. 11 Compensation functions of individual participants in Exp. 3

may be too simple. In fact, it has already been elaborated by the addition of a second-order correction term (Semjen et al., 1998; Pressing & Jolley-Rogers, 1997; Pressing, 1998), and it is possible that this new model can account for the individual functions shown here. A more detailed exploration of this issue is beyond the scope of this paper, however.

Experiment 4

Experiment 4 investigated a different variable that has been found to affect the detectability of IOI increments in music: When listeners are exposed to an expressively timed music performance in which IOI durations are not constant but vary systematically, then detection of IOI increments in a subsequent metronomic performance of the same music is significantly impaired (Repp, 1998b: Exp. 1). Experiment 4 examined whether the error correction process would also be less effective under the same circumstances.

Although Repp (1998b) employed musical stimuli, the effect of a temporally modulated precursor is not believed to be specific to music. Informal observations suggest that it is obtained with sequences of short tones as well. A related finding has been reported by Large and Jones (1999), who attributed it to the widening of the temporal "expectancy region" of an attentional oscillator. This implies a greater perceptual tolerance for deviations from regularity. In the context of a synchronization task, it may mean greater variability of the central timekeeper and perhaps less reliable registration of small phase errors and hence less effective compensation.

Method

Participants. The participants were the same as in Exps. 1 and 3.

Materials and procedure. The stimuli of Exp. 3 with 10-ms increments were used again. Each trial, however, was preceded by a computer-synthesized expressive performance of the Chopin *Etude* excerpt. This performance is described in more detail in Repp (1998b). Here it suffices to note that its IOIs varied in duration over a range of approximately 300 ms, in a pattern that was somewhat unusual but similar to that of performances by some distinguished pianists. The participants just listened to this performance before tapping in synchrony with a subjectively metronomic version of the music containing four IOI increments. There were five blocks of ten trials each, with each trial being preceded by the same precursor. All other details of procedure and data analysis were the same as in Exp. 3.

Results and discussion

Figure 12 compares the average compensation function of Exp. 4 ("with precursor") with that of Exp. 3 ("without precursor"). It is obvious that repeated exposure to an expressively timed performance did not interfere with error correction. If anything, error correction was slightly more effective in Exp. 3, being complete within two taps, on the average. However, this difference was not consistent across participants and hence not significant in a repeated-measures ANOVA. Likewise, there was no evidence of any increase in response variability relative to Exp. 3: Six participants showed small decreases in variability, perhaps due to practice, and only one showed a considerable increase. The range of individual average standard deviations was from 15 to 28 ms.

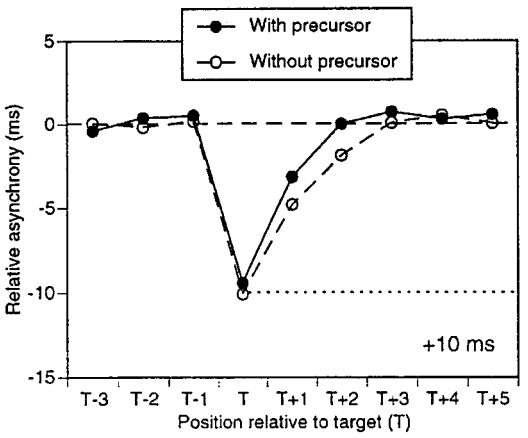

Fig. 12 Average compensation functions for 10-ms increments in Exps. 4 ("with precursor") and 3 ("without precursor")

These results suggest that a nonstationary precursor has no effect on the variability of the phase error or on the efficiency of phase error correction. The interpretation of Large and Jones (1999), which attributes the precursor effect to a widened expectancy region of an attentional oscillator, evidently has implications only for explicit detection, but not for automatic error correction in synchronization, which takes place without attention. The automatic error correction process feeds on small differences within the expectancy region, regardless of the width of that region. This is not inconsistent with the model of Large and Jones, because their oscillator exhibits maximum sensitivity near the expected time of an event.

Experiment 5

Experiment 5 continued the thrust of Exps. 3 and 4 by examining the influence on automatic compensation of yet another factor that was expected to inhibit the explicit detection of timing deviations. Several studies have demonstrated that, if tones arranged in an isochronous sequence abruptly change in pitch or timbre, a deviation from isochrony is more difficult to detect at the point of change than within each of the two homogenous parts (Fitzgibbons, Pollatsek & Thomas, 1974; Thorpe, Trehub, Morrongiello & Bull, 1998; Hirsh, Monahan, Grant, & Singh 1990; Drake, 1993), presumably due to

perceptual grouping or source segregation at an early stage in auditory processing. A deterioration of temporal discrimination acuity, though mainly for very short durations, has also been found with increasing frequency separation of two tones delimiting a single temporal interval (e.g., Perrott & Williams, 1971; Divenyi & Danner, 1977; Divenyi & Sachs, 1978). In addition to this effect on sensitivity, a bias effect has been described in the literature, in that temporal intervals separating two groups of sounds tend to be perceived as longer than physically equal within-group intervals (Thorpe et al., 1988; Thorpe & Trehub, 1989). Also, a single temporal interval delimited by two tones separated widely in frequency tends to be perceived as longer than a physically equal interval delimited by two tones more similar in frequency (Shigeno, 1986, 1993; Crowder & Neath 1995). These latter findings led to the expectation that, between auditory groups, an IOI decrement would be even more difficult to detect than an IOI increment, because a decrement neutralizes rather than reinforces the bias.

Experiment 5 compared motor compensation for pulse-type changes that occurred either between or within auditory groups in a sequence. If, as Exps. 3 and 4 suggested, the error correction process is independent of factors that influence explicit detection of timing perturbations, then compensation should also be equally effective for perturbations between and within groups. If so, this would imply that the phase errors are unaffected and that the effects of pitch distance and grouping are specific to explicit interval perception and judgement.

Experiment 5 also addressed a second question, namely whether the time course of compensation is different for subliminal and supraliminal temporal changes – or, in other words, whether it is modified (most likely, accelerated) by the conscious awareness of a perturbation. It was noted earlier that the average compensation functions for the almost entirely subliminal changes in Exp. 3 were more gradual than those for the largely supraliminal changes in the similar experiment of Repp (1999a), and that Thaut et al. (1998a) had found more rapid phase error correction for large than for small step changes in a sequence. Reverting to simple sequences of tones, Exp. 5 introduced a range of pulse change magnitudes, both IOI increments and decrements, that straddled the expected interval discrimination threshold. To determine this threshold and its sensitivity to grouping, a combined synchronization and detection task was employed in which participants had to indicate whether they had perceived any perturbation in the sequence they had just tapped along with.

The detection task not only served to demonstrate the different detectability of within- and between-group changes, but it was also expected to confirm that the small changes in Exp. 1 had been truly subliminal. Although these changes had clearly been below the threshold established in psychophysical experiments, the possibility had to be considered that synchronized tapping facilitates explicit detection of timing perturbations. However, Exp. 5 was expected to confirm that the average detection threshold for within-group pulse changes is at about 4% of the baseline IOI for musically trained listeners.

Finally, the results of the detection task also made it possible to compare trials on which a change had been detected with physically identical trials on which the change had not been detected – that is, to separate the effect of explicit detection from that of the magnitude of the change.

Method

Participants. Six of the eight participants in Exps. 1, 3, and 4 returned for another session.

Materials. Each trial in this experiment comprised 20 or 24 short tones with a baseline IOI of 500 ms. The first 10 or 14 tones were the same as in Exp. 1, representing the musical pitch C_8 (MIDI pitch 108, fundamental frequency 4,168 Hz) produced on the Roland RD-250s digital piano. The remaining 10 tones represented the pitch E_7 (MIDI pitch 100, fundamental frequency 2,638 Hz). These pitches were 8 semitones apart, a considerable and clearly audible difference. The IOI delimited by tones of different frequency will be referred to as "the break." On every trial, a single change in IOI duration of size Δt occurred in one of two locations: after the 10th tone or after the 14th tone. Since the break also occurred either after the 10th or after the 14th tone, there were four types of trials: two in which the pulse-type change occurred in the break, and two in which it did not. There were 10 magnitudes of Δt ranging from −10 to −30 ms (decrements) and from +10 to +30 ms (increments) in steps of 5 ms. Ten magnitudes and four trial types resulted in 40 trials, which were presented five times in different random orders, arranged in 10 blocks of 20 trials each.

Procedure. The equipment and procedure for the synchronization task were the same as in the preceding experiments. In addition, however, immediately after each trial, participants pressed one of three keys on the computer keyboard to indicate whether they had detected a shortened interval (*left-arrow*), no change (*down-arrow*), or a lengthened interval (*right-arrow*) in the sequence. The participants were informed that there was one change in each trial, but guessing was discouraged. The keypress information from the computer keyboard was saved with the tapping data and triggered the presentation of the next trial, which started 4 s later.

Results and discussion

The results of the detection task are shown in Fig. 13 in in terms of the average percentages of correct positive responses. (Incorrect positive responses were rare.) Contrary to expectations, an effect of the break between auditory groups was obtained only for IOI increments (as demonstrated previously by Thorpe et al., 1988, and Thorpe & Trehub, 1989), but not for IOI decrements (apparently a novel result). A three-way repeated-measures ANOVA on the data (with the factors of break, direction of change, and absolute magnitude of change) showed no significant effect of break overall, but significant interactions between break and direction of change, $F(1,5) = 10.97$, $p < .03$, and between break

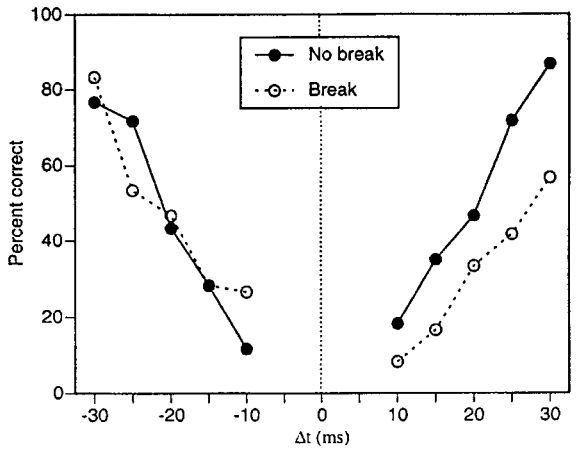

Fig. 13 Results of the detection task in Exp. 5: Percent correct detection as a function of magnitude of change and of whether or not the change fell in the break between two subsequences differing in pitch

and absolute magnitude of change, $F(4,20) = 5.58$, $p < .004$. A separate two-way ANOVA on the increment data showed the main effect of break to be significant, $F(1,5) = 14.57$, $p < .02$. Another way of describing these results is that, in the break, IOI decrements were easier to detect than IOI increments, whereas within auditory groups the opposite was true. While the within-group difference is consistent with earlier results (Repp, 1998a), the between-group difference is inconsistent with the claim of Thorpe et al. (1998) and Thorpe and Trehub (1989) that the between-group IOI is perceived as longer than within-group IOIs. If anything, the results suggest that the IOI between groups is *expected* to be longer and hence is perceived as *shorter* than the surrounding intervals (cf. Repp, 1992, 1998a).

The detection results confirmed the expected detection threshold (50% correct), which for both increments and decrements was in the vicinity of 20–25 ms, or 4–5% of the baseline IOI. Thus, there was no reason to believe that synchronized tapping somehow enhanced the detectability of timing perturbations beyond that typically reported in the psychophysical literature. Given the absence of an effect of the break on IOI decrement detection, only the synchronization data for IOI increments were relevant to the hypothesis that the break might affect error correction in tapping. However, all data remained relevant to the hypothesis that explicit detection might interact with error correction.

The average asynchronies in the various Δt conditions are shown in Figs. 14 (IOI increments) and 15 (IOI decrements). As in Exp. 1, the asynchronies of each participant were first relativized by subtracting the average asynchrony of the three positions preceding a target (T). Sequences in which the target occurred after the 10th tone were aligned and averaged with those in which it occurred after the 14th tone, and the data were truncated before position T − 3 and after position T + 6. Each panel in the figures contrasts the trials in which the

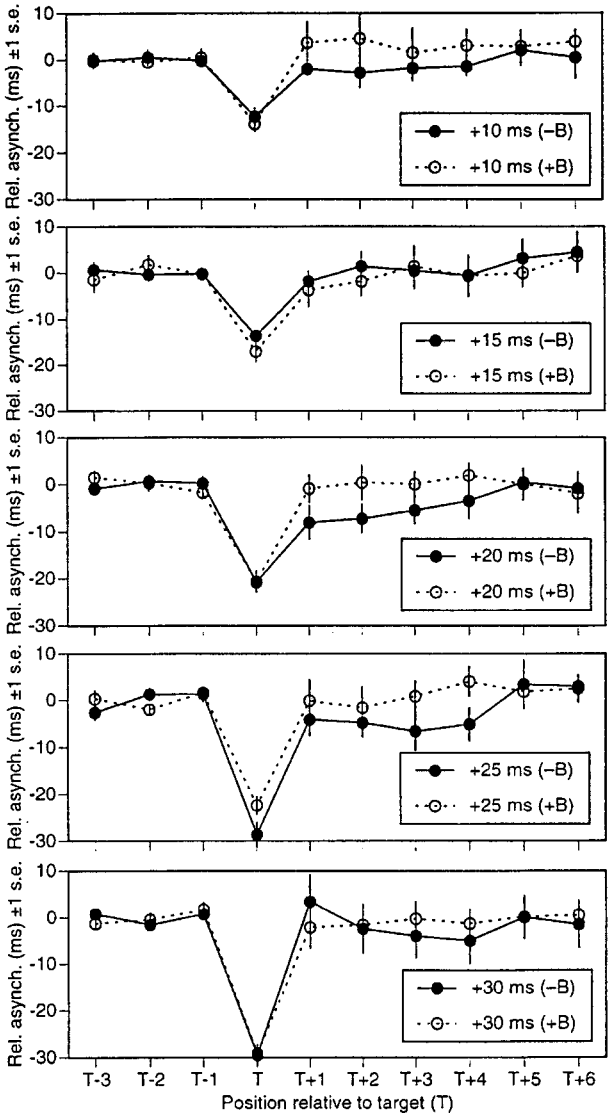

Fig. 14 Average compensation functions for five increment sizes in Exp. 5, separately for changes that occurred in the pitch break (+B) and that occurred away from the break (−B)

target occurred in the break (+B) with those in which it occurred away from the break (−B). The error bars represent *single* standard errors, because the difference between the two conditions is of interest here. Non-overlapping standard error bars suggest a significant local difference.

The data in Fig. 14 show that compensation for increments was immediate for all magnitudes of Δt. Moreover, there were few significant differences between the −B and +B conditions. These occurred in the 20-ms and 25-ms conditions and suggested, if anything, that compensation was *more* effective when the increment fell in the break. In the 25-ms condition, however, there was a surprising difference in the target position itself, for unknown reasons. On the whole, these results look more like those of Repp (1999a) than those of Exps. 1, 3, and

4, which showed more gradual compensation for increments. Although the increasing practice of the participants and the presence of only a single perturbation per trial could explain the difference from the earlier experiments, it does not explain the similarity with Repp's (1999a) data, which derived from unpracticed participants and four targets per trial.

The data in Fig. 15 show that compensation for decrements was more gradual than for increments. Even though no differences between the −B and +B conditions were expected here, given the absence of a reliable difference in detectability (Fig. 13), there were some significant differences in the 10-ms and 15-ms decrement conditions, indicating that compensation was more gradual when the decrement fell in the break. In the 10-ms condition, however, there was also a significant difference in the target position, which again is difficult to interpret. Moreover, the gradual compensation for short decrements in the 10-ms and 15-ms +B conditions is consistent with the gradual compensation for longer decrements, whereas the seemingly immediate compensation for short decrements in the −B conditions is the anomaly to be explained. Whatever the explanation may be, it is clear that compensation was as effective at small sizes as at large sizes of Δt and hence also unaffected by detectability. No changes in compensation strategy contingent on Δt magnitude are evident, such as observed by Thaut et al. (1998a) for step changes.

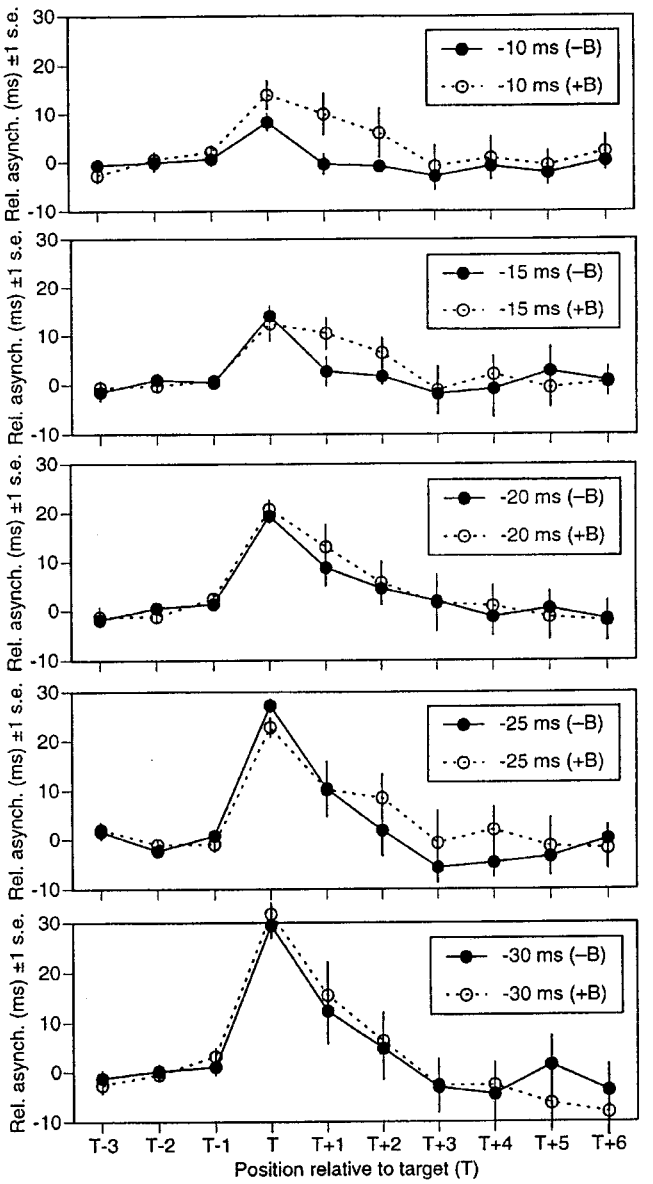

Fig. 15 Average compensation functions for five decrement sizes in Exp. 5, separately for changes that occurred in the pitch break (+B) and away from the break (−B)

An additional analysis pertinent to the role of explicit detection was conducted. For each participant, the trials for 20-ms and 25-ms increments and decrements (the ones closest to the detection threshold) were divided into those on which the direction of change was reported correctly and those on which no change (or, rarely, a change in the incorrect direction) was reported. The compensation functions for trials of each type were averaged after aligning the trials with different locations of change. Finally, these individual averages were relativized and averaged across participants, and standard errors were calculated. The results are shown in Fig. 16.

There were some unexpected and puzzling differences here, probably due to the very uneven division of trials for some participants and the small number of trials in general: In the 25-ms increment condition, asynchronies in the *target* position were much shorter when the change was not detected than when it was detected, and this difference persisted over the following positions. A smaller difference in the opposite direction was found in the 25-ms decrement condition. Taken by themselves, these differences would suggest that the target asynchrony itself was a factor in the detection of the change; however, there was no trace of such a difference in either of the 20-ms conditions. The 20-ms conditions instead suggest that compensation was less effective when the change was not detected, especially in the case of decrements. In the 25-ms conditions, by contrast, there was no such trend at all. These results, then, are not internally consistent and give no reason to modify the conclusion that the speed of compensation was independent of the detectability of the timing change.

Finally, the time course of compensation was examined as to whether it resembled the exponential function that is implied by the phase error correction model of Vorberg & Wing (1996). Compensation for increments was immediate and complete in this experiment, so the question could be asked only for decrements. These data, normalized to the range from 1 to 0 and averaged across all Δt sizes (as in Fig. 4), are displayed in Fig. 17. The double standard errors represent the variation among the five Δt conditions. The dashed exponential function ($a = 0.5$) has been fitted to the three initial data points only, as the following data points are slightly negative. It is evident that the initial time course of

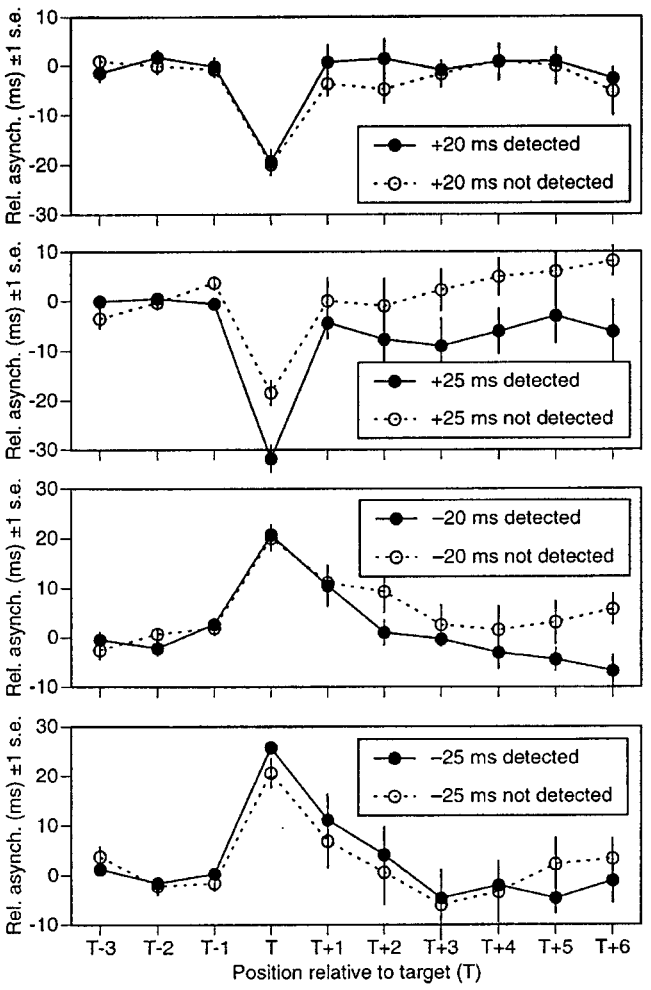

Fig. 16 Average compensation functions for trials on which a change was detected and for trials on which no change (or an incorrect change) was detected, for 20- and 25-ms increments and decrements in Exp. 5

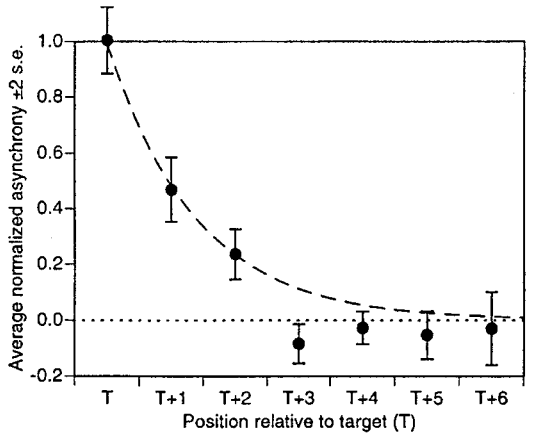

Fig. 17 Grand average normalized compensation function for all decrement conditions in Exp. 5. The *dashed curve* is the best-fitting exponential curve for the initial three data points

compensation is very compatible with the exponential model; in fact, the first three normalized values are almost identical with those in Exp. 1. However, in position T + 3 there is a significant deviation from the exponential curve: Compensation was faster than predicted; in fact, there was a slight overcompensation at that point. This contrasts with the undercompensation observed in Exp. 1 (Fig. 4). The reason for this difference between experiments is not clear, but the deviation from the exponential model is fairly striking. This suggests that the simple phase correction model is not fully adequate, although perhaps the second-order model of Semjen et al. (1998) and Pressing (1998) could handle these results.

General discussion

The present research was begun with the intention of refuting the hypothesis that only stimulus changes that are explicitly detected lead to error correction in synchronized tapping. Admittedly, this hypothesis (TH2) was a bit simple-minded and had not been seriously proposed by anyone in the literature. Nevertheless, it is in accord with a general tendency, discussed by Neumann (1990), to assume that conscious perception intervenes between sensation and action. Also, with the exception of the very recent work by Thaut et al. (1998a, 1998b), previous studies of perceptual-motor synchronization have paid little attention to the relation between error correction and the interval discrimination threshold. That the hypothesis possesses some intuitive plausibility, at least for relative novices in this area of research, is illustrated by the author's surprise and excitement when he first discovered that subliminal stimulus changes are compensated for (Repp, 1999a) as well as by comments he has received from several colleagues.

Experiment 1 clearly demonstrated that this general hypothesis is incorrect. Pulse changes in stimulus timing that were well below the explicit detection threshold led to effective adjustments in the timing of the motor response. Thaut et al. (1998a,b) drew similar conclusions from investigations involving step changes or periodic perturbations of the stimulus period. Experiment 5 ruled out the unlikely possibility that synchronized tapping somehow leads to perceptual hypersensitivity for pulse changes in IOI duration. That experiment also established that compensation for pulse changes is essentially independent of whether or not they are detected, at least within a narrow range of Δt sizes in the vicinity of the detection threshold. Although explicit detection seemed to facilitate compensation somewhat in certain conditions, these results were not consistent and need to be replicated before they are taken seriously.

Experiments 3 and 4 showed that compensation for subliminal pulse changes occurs not only in simple sequences but in music as well. Experiments 3–5 went further by demonstrating that compensation is unaffected by three factors that are known to influence the explicit

detection threshold. In Exp. 3, motor compensation for subliminal pulse changes was just as effective in positions in which larger changes were difficult to detect as in positions in which they were easy to detect (according to data from Repp, 1999a). Experiment 4 showed that exposure to a temporally modulated precursor does not inhibit compensation for subliminal IOI increments in an isochronous musical excerpt, even though it seems to inhibit explicit detection across the board (Repp, 1998b: Exp. 1; Large & Jones, 1999). Experiment 5 showed that a large pitch change within a stimulus sequence does not affect compensation for IOI increments that coincide with it, even though it lowers their detectability.

Although these findings demonstrate that subliminal stimulus changes are compensated for, it would be wrong to conclude that motor compensation occurred on the basis of subliminal perceptual information about changes in stimulus IOI duration. Such information would be relevant only to timekeeper period correction, and there is no reason to assume that such correction occurred in the present paradigm. The observed compensation was most likely a phase adjustment based on perception of the synchronization error. Therefore, the present results are irrelevant to the hypothesis called here TH2. Rather, they bear on the alternative threshold hypothesis, called here TH1, which claims that perception of the phase error as a source of information for error correction is limited by a perceptual threshold.

The preceding argument is based on the assumptions underlying the two-level model of Vorberg and Wing (1996), according to which local adjustments in timekeeper period (equivalent to phase resetting) can be made independently of central period adjustments. If this model is not adopted, the argument may not hold. Obviously, in order to compensate for any change in the stimulus (pulse, step, or continuous modulation), it is necessary to adjust the *response* period, and in this sense period correction is always involved. Thaut et al. (1998a,b) have proposed a single-level model in which period correction has this particular meaning. They believe that unless it is very large the phase error is too variable to provide useful information for error correction. Thus, they are subscribing to a version of TH1, while at the same time arguing against TH2. However, their data really only bear on the more general hypothesis that compensation is limited by some perceptual threshold, because in their model, period and phase error correction are not independent. Nevertheless, since timekeeper period adjustment in the sense of the two-level model is highly likely in step change and continuous modulation paradigms, the results of Thaut et al. probably do provide evidence against TH2, whereas the present data do not. Rejection of TH2 implies that highly accurate temporal stimulus information can be accessed in the brain for purposes of motor control before it is contaminated by the "perceptual noise" that limits explicit interval and tempo discrimination.

The present results make it possible to draw an analogous conclusion with regard to the phase error and to reject TH1, the threshold hypothesis commonly stated in the literature (Michon, 1967; Voillaume, 1971; Mates, 1994b; Vorberg & Wing, 1996). Experiment 2 demonstrated that five out of six participants had great difficulty in explicitly judging the directions of their phase errors, yet they showed compensation in Exp. 1. Moreover, the binned analysis of the Exp. 1 data suggested that phase errors of all sizes are compensated for. This leads to the conclusion that phase error correction is not limited by an explicit or implicit temporal order threshold, and that it may not be necessary to incorporate such a threshold into a formal model of error correction, as Mates (1994b) has done.

Although the present results are compatible with the basic assumptions underlying the two-level phase error correction model of Vorberg and Wing (1996), they deviate in two ways that may necessitate modifications of the model. One finding was that individual compensation functions are more often linear than exponential in shape (at least when the stimulus is music), and even average compensation functions do not always fit an exponential curve. The other finding was a statistical dependency between the pre-target baseline asynchronies and the asynchrony in position T. Perhaps models with higher-order error correction terms (Semjen et al. 1998 and Pressing, 1998) will be able to account for these findings. The possibility of systematic drift in asynchronies also needs to be considered.

The average time course of compensation varied from experiment to experiment and among participants. The reasons for the variation across experiments are not currently understood. The individual differences, with the oldest (but most practiced) participant consistently showing the slowest compensation, suggest an influence of age that would be worth studying in more detail.

The results of Exps. 3–5 suggest that factors that affect conscious interval perception do not affect the phase error, which depends on the onset times of the events delimiting intervals. This means that there is a level of interval perception distinct from onset perception. Thus, for example, even though the IOI separating two auditory groups may be perceived as subjectively short (as inferred from the results of Exp. 5, contrary to Thorpe & Trehub, 1989), the second group is not perceived as starting early, at least not in terms of subconsciously processed phase errors. (The possibility remains that it would be so perceived in terms of explicit temporal-order judgments.)

The most general conclusion from the present results and from those of Thaut et al. (1998a,b) is that the temporal information available to the timekeeping and feedback mechanisms in perceptual-motor synchronization is considerably more accurate than the one that enables a listener to explicity detect deviations from temporal regularity or the temporal order of two events. Perceptual-motor synchronization in the presence of small timing perturbations provides an instance of action making use of sensory information without the mediation of conscious perception. This has been

referred to as direct perception-action coupling (e.g., Kelso & Kay, 1987), direct parameter specification (Neumann, 1990), or entrainment (e.g., Thaut et al., 1998b). The present results and those of Thaut et al. also raise interesting questions about the brain structures subserving timing perception and timing control in action, a research area in which there is increasing activity (see, e.g., Ivry & Keele, 1989; Goodale & Milner, 1992; Rao et al., 1997; Harrington, Haaland & Hermanowicz, 1998; Harrington, Haaland & Knight, 1998). Goodale and his coworkers have found evidence for separate visual pathways pertaining to object perception and the control of action (Goodale & Milner, 1992; Goodale & Humphrey, 1998). While such an anatomical dissociation may not exist in the auditory system, it seems nevertheless likely that incoming temporal information is accessed earlier by the brain systems that control automatic action than by those that lead to conscious perception, and that the additional neural transmission and processing required for the latter leads to greater temporal uncertainty, as proposed by Rosenbaum (1998) in his "broadcast theory" of timing.

Acknowledgements This research was supported by NIH Grant MH-51230. Thanks to Paul Buechler for extensive assistance and to Gisa Aschersleben, Lawrence Parsons, Jeff Pressing, Andras Semjen, Dirk Vorberg, Michael Thaut, and Michael Turvey for helpful comments or discussions.

Note added in proof An excellent study by Koch (1999) came to the author's attention after this article had gone to press. Koch showed that participants' ability to detect asynchronies between clicks and taps in a synchronization task is initially very poor, in agreement with the present Exp. 2, but improves considerably with practice. In an analysis similar to that presented in the present Figs. 5 and 6, he also obtained evidence that undetected asynchronies affect the timing of the subsequent tap.

Koch, R. (1999). Detection of asynchrony between click and tap. Paper 1/1999, Max Planck Institute for Psychological Research, Munich.

References

Allan, L. G. (1975a). The relationship between judgments of successiveness and judgments of order. *Perception & Psychophysics, 18*, 29–36.

Allan, L. G. (1975b). Temporal order psychometric functions based on confidence-rating data. *Perception & Psychophysics, 18*, 369–372.

Aschersleben, G., & Prinz, W. (1995). Synchronizing actions with events: The role of sensory information. *Perception & Psychophysics, 57*, 305–317.

Aschersleben, G., & Prinz, W. (1997). Delayed auditory feedback in synchronization. *Journal of Motor Behavior, 29*, 35–46.

Clarke, E. F. (1989). The perception of expressive timing in music. *Psychological Research, 51*, 2–9.

Collyer, C. E., Boatright-Horowitz, S. S., & Hooper, S. (1997). A motor timing experiment implemented using a musical instrument digital interface (MIDI) approach. *Behavior Research Methods, Instruments, & Computers, 29*, 346–352.

Crowder, R. G., & Neath, I. (1994). The influence of pitch on time perception in short melodies. *Music Perception, 12*, 379–386.

Divenyi, P. L., & Danner, W. F. (1977). Discrimination of time intervals marked by brief acoustic pulses of various intensities and spectra. *Perception & Psychophysics, 21*, 125–142.

Divenyi, P. L., & Sachs, R. M. (1978). Discrimination of time intervals bounded by tone bursts. *Perception & Psychophysics, 24*, 429–436.

Drake, C. (1993). Perceptual and performed accents in musical sequences. *Bulletin of the Psychonomic Sciences, 31*, 107–110.

Drake, C., & Botte, M.-C. (1993). Tempo sensitivity in auditory sequences: Evidence for a multiple-look model. *Perception & Psychophysics, 54*, 277–286.

Fitzgibbons, P. J., Pollatsek, A., & Thomas, I. B. (1974). Detection of temporal gaps within and between perceptual tonal groups. *Perception & Psychophysics, 16*, 522–528.

Fraisse, P. (1966). L'anticipation de stimulus rythmiques: Vitesse d'établissement et précision de la synchronisation. *L'Année Psychologique, 66*, 15–36.

Friberg, A., & Sundberg, J. (1995). Time discrimination in a monotonic, isochronous sequence. *Journal of the Acoustical Society of America, 98*, 2524–2531.

Goodale, M. A., & Humphrey, G. K. (1998). The objects of action and perception. *Cognition, 67*, 181–207.

Goodale, M. A., & Milner, D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences, 15*, 20–25.

Green, D. M., & Swets, J. A. (1996). *Signal detection theory and psychophysics*. Huntington, NY: Krieger.

Halpern, A. R., & Darwin, C. J. (1982). Duration discrimination in a series of rhythmic events. *Perception & Psychophysics, 31*, 86–89.

Harrington, D. L., Haaland, K. Y., & Hermanowicz, N. (1998). Temporal processing in the basal ganglia. *Neuropsychology, 12*, 3–12.

Harrington, D. L., Haaland, K. Y., & Knight, R. T. (1998). Cortical networks underlying mechanisms of time perception. *The Journal of Neuroscience, 18*, 1085–1095.

Hary, D., & Moore, G. P. (1985). Temporal tracking and synchronization strategies. *Human Neurobiology, 4*, 73–77.

Hary, D., & Moore, G. P. (1987). Synchronizing human movement with an external clock source. *Biological Cybernetics, 56*, 305–311.

Hibi, S. (1983). Rhythm perception in repetitive sound sequence. *Journal of the Acoustical Society of Japan (E), 4*, 83–95.

Hirsh, I. J. (1959). Auditory perception of temporal order. *Journal of the Acoustical Society of America, 31*, 759–767.

Hirsh, I. J., & Sherrick, C. E., Jr. (1961). Perceived order in different sense modalities. *Journal of Experimental Psychology, 62*, 423–432.

Hirsh, I. J., Monahan, C. B., Grant, K. W., & Singh, P. G. (1990). Studies in auditory timing: I. Simple patterns. *Perception & Psychophysics, 47*, 215–226.

Ivry, R. B., & Hazeltine, R. E., (1995). Perception and production of temporal intervals across a range of durations: Evidence for a common timing mechanism. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 3–18.

Ivry, R. B., & Keele, S. W. (1989). Timing functions of the cerebellum. *Journal of Cognitive Neuroscience, 1*, 136–152.

Keele, S. W., Pokorny, R. A., Corcos, D. M., & Ivry, R. (1985). Do perception and motor production share common timing mechanisms: A correlational analysis. *Acta Psychologica, 60*, 173–191.

Kelso, J. A. S., & Kay, B. A. (1987). Information and control: A macroscopic analysis of perception-action coupling. In H. Heuer & A.F. Sanders (Eds.), *Perspectives on perception and action* (pp. 3–32). Hillsdale, NJ: Erlbaum.

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people time-varying events. *Psychological Review, 106*, 119–159.

Mates, J. (1994a). A model of synchronization of motor acts to a stimulus sequence: I. Timing and error corrections. *Biological Cybernetics, 70*, 463–473.

Mates, J. (1994b). A model of synchronization of motor acts to a stimulus sequence: II. Stability analysis, error estimation and simulations. *Biological Cybernetics, 70*, 475–484.

McAuley, J. D., & Kidd, G. R. (1998). Effect of deviations from temporal expectations on tempo discrimination of isochronous tone sequences. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1786–1800.

Michon, J. A. (1967). *Timing in temporal tracking*. Assen, NL: van Gorcum.

Neumann, O. (1990). Direct parameter specification and the concept of perception. *Psychological Research, 52*, 207–215.

Palmer, C., & Brown, J. C. (1991). Investigations in the amplitude of sounded piano tones. *Journal of the Acoustical Society of America, 90*, 60–66.

Perrott, D. R., Williams, K. N. (1971). Auditory temporal resolution: Gap detection as a function of interpulse frequency disparity. *Psychonomic Science, 25*, 73–74.

Peters, M. (1989). The relationship between variability of intertap intervals and interval duration. *Psychological Research, 51*, 38–42.

Pressing, J. (1998). Error correction processes in temporal pattern production. *Journal of Mathematical Psychology, 42*, 63–101.

Pressing, J. (1999). The referential dynamics of cognition and action. *Psychological Review, 106*, 714–747.

Pressing, J., & Jolley-Rogers, G. (1997). Spectral properties of human cognition and skill. *Biological Cybernetics, 76*, 339–347.

Rao, S. M., Harrington, D. L., Haaland, K. Y., Bobholz, J. A., Cox, R. W., & Binder, J. R. (1997). Distributed neural systems underlying the timing of movements. *The Journal of Neuroscience, 17*, 5528–5535.

Repp, B. H. (1992). Probing the cognitive representation of musical time: Structural constraints on the perception of timing perturbations. *Cognition, 44*, 241–281.

Repp, B. H. (1998a). Variations on a theme by Chopin: Relations between perception and production of timing in music. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 791–811.

Repp, B. H. (1998b). Obligatory "expectations" of expressive timing induced by perception of musical structure. *Psychological Research, 61*, 33–43.

Repp, B. H. (1999a). Detecting deviations from metronomic timing in music: Effects of perceptual structure on the mental timekeeper. *Perception & Psychophysics, 61*, 529–548.

Repp, B. H. (1999b). Control of expressive and metronomic timing in pianists. *Journal of Motor Behavior, 31*, 145–164.

Repp, B. H. (1999c). Relationships between performance timing, perception of timing perturbations, and perceptual-motor synchronization in two Chopin preludes. *Australian Journal of Psychology, 51*, 188–203.

Rosenbaum, D. A. (1998). Broadcast theory of timing. In D.A. Rosenbaum & C.E. Collyer (Eds.), *Timing of behavior: Neural, psychological, and computational perspectives* (pp. 215–235). Cambridge, MA: MIT Press.

Semjen, A., Vorberg, D., & Schulze, H.-H. (1998). Getting synchronized with the metronome: Comparisons between phase and period correction. *Psychological Research, 61*, 44–55.

Shigeno, S. (1986). The auditory tau and kappa effects for speech and nonspeech stimuli. *Perception & Psychophysics, 40*, 9–19.

Shigeno, S. (1993). The interdependence of pitch and temporal judgements by absolute pitch possessors, *Perception & Psychophysics, 54*, 682–692.

Tecchio, F., Salustri, C., Thaut, M. H., Pizzella, V., Romani, G.-L., & Rossini, P. M. (1998). *Rhythmic auditory stimuli: A MEG study of cerebral responses to unconscious and conscious adaptation*. Manuscript submitted for publication.

Thaut, M. H., Miller, R. A., & Schauer, L. M. (1998a). Multiple synchronization strategies in rhythmic sensorimotor tasks: Phase vs. period correction. *Biological Cybernetics, 79*, 241–250.

Thaut, M. H., Tian, B., & Azimi-Sadjadi, M. R. (1998b). Rhythmic finger tapping to cosine-wave modulated metronome sequences: Evidence of subliminal entrainment. *Human Movement Science, 17*, 839–863.

Thorpe, L. A., & Trehub, S. E. (1989). Duration illusion and auditory grouping in infancy. *Developmental Psychology, 25*, 122–127.

Thorpe, L. A., Trehub, S. E., Morrongiello, B. A., & Bull, D. (1988). Perceptual grouping by infants and preschool children. *Developmental Psychology, 24*, 484–491.

Vaughan, J., Rosenbaum, D. A., Diedrich, F. J., & Moore, C. M. (1996). Cooperative selection of movements: The optimal selection model. *Psychological Research, 58*, 254–273.

Vaughan, J., Mattson, T. R., & Rosenbaum, D. A. (1998). The regulation of contact in rhythmic tapping. In D.A. Rosenbaum & C.E. Collyer (Eds.), *Timing of behavior: Neural, psychological, and computational perspectives* (pp. 195–211). Cambridge, MA: MIT Press.

Voillaume, C. (1971). Modèles pour l'étude de la régulation des mouvements cadencés. *L'Année Psychologique, 71*, 347–358.

Vorberg, D., & Wing, A. (1996). Modeling variability and dependence in timing. In H. Heuer & S.W. Keele (Eds.), *Handbook of perception and action* (Vol. 2, pp. 181–262). London: Academic Press.

Wing, A. M. (1977a). Perturbations of auditory feedback delay and the timing of movement. *Journal of Experimental Psychology: Human Perception and Performance, 3*, 175–186.

Wing, A. M. (1977b). Effects of type of movement on the temporal precision of response sequences. *British Journal of Mathematical and Statistical Psychology, 30*, 60–72.

Wing, A. M. (1980). The long and short of timing in response sequences. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 469–486). Amsterdam: North-Holland.

Wing, A. M., & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses. *Perception & Psychophysics, 14*, 5–12.