

Subliminal temporal discrimination revealed in sensorimotor coordination

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Introduction

The perception of sensory information is subject to limits that have been established in many psychophysical experiments. These limits often reflect the resolving power of the sensory organs. The perception of temporal information, however, is a special case because there is no specific organ for it and hence no obvious peripheral limit to sensory resolution. Nevertheless, small temporal differences often are not detected by perceivers. This must reflect limits imposed by processes in the brain.

Two kinds of temporal threshold are pertinent to the present study: for differences in interval duration, and for the temporal order of two events. Although the interval discrimination threshold depends on the paradigm used and on the training of the participants, it is rarely below 4% for changes in single intervals or event onsets in an isochronous sequence (Hibi, 1983; Halpern and Darwin, 1982; Clarke, 1989; Drake, 1993; Repp, 1999). Weber's law seems to hold approximately for durations between 300 and 1000 ms (see Friberg and Sundberg, 1995). Thus, when a sequence of 500-ms intervals is presented to moderately sensitive listeners, a single change of ± 20 ms will be detected about 75% of the time on the average in a forced-choice paradigm or 50% of the time in a vigilance paradigm, whereas a change of ± 10 ms or less will hardly ever be detected.

Classic research by Hirsh (1959) has demonstrated that an onset asynchrony of about 20 ms is necessary for listeners to identify the temporal order of two different sounds correctly about 75% of the time (50% being chance). This temporal order threshold seems to be similar in different modalities and even across modalities (Hirsh and Sherrick, 1961). It needs to be distinguished from the non-simultaneity threshold, which may be smaller, especially within the auditory modality. The present study, however, is concerned only with cross-modal (kinesthetic-auditory) temporal order perception.

The task of interest is perceptual-motor synchronization. The stimulus is an isochronous sequence of tones, and the participant taps along on a silent response key, trying to minimize the temporal differences between the subjective times of occurrence of the tones and of the taps (i.e., the synchronization or phase errors). This requires perception of the temporal order of tone and tap because positive and negative phase errors require different corrective actions. Since the average objectively measured asynchrony in synchronization tasks is typically negative, meaning that taps tend to precede tone onsets (see, e.g., Aschersleben and Prinz, 1995), it must be assumed that the point of subjective simultaneity (PSS) corresponds to the mean asynchrony and that the temporal order of tone and tap is perceived relative to the PSS (see Mates, 1994a).

In an interesting theoretical article, Neumann (1990) has pointed out a widespread tendency to assume (often tacitly) that conscious perception mediates between sensory input and action. That assumption is reflected in the literature on perceptual-motor synchronization. For example, Michon (1967) believed 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 and Sherrick, 1961), no action will be taken" (p. 84). In other words, only phase errors that exceed the temporal order threshold will be compensated for. This assumption has been reiterated or made independently by other authors, such as Voillaume (1971), Mates (1994b), Vorberg and Wing (1996), Pressing and Jolley-Rogers (1997), and Thaut, Miller and Schauer (1998a). Mates (1994b) was the only one to implement the threshold assumption in a formal model of error correction and show that this model accounts 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 mechanism (Mates, 1994a). Other researchers in this area, such as Hary and Moore (1985, 1987), Pressing (1998), and Large and Jones (1999), do not make a threshold assumption, but neither do they discuss why they find perceptual thresholds irrelevant. Thus the empirical support for the hypothesis that the temporal order threshold limits error correction in synchronization is quite limited. At the same time, there has been little evidence to the contrary.

To maintain synchrony with a stationary (isochronous) stimulus sequence, all that is required is a process of phase correction which, according to a popular two-tiered model, adjusts the intervals generated by an internal timekeeper without changing the timekeeper period (Vorberg and Wing, 1996; Semjen, Vorberg and Schulze, 1998; Pressing, 1998). 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 assumes period correction only, in order to account for tracking behavior (i.e., when

tap timing echoes stimulus timing at a lag of one). Surprisingly, authors concerned with period correction have made no reference to the interval (or tempo) discrimination threshold, which constrains the conscious detection of a change in the stimulus period. Nevertheless, in synchronization with nonstationary sequences, the interval discrimination and temporal order thresholds seem both relevant and perhaps impose limits on two distinct mechanisms of error correction.

One way of testing the role of perceptual thresholds in a synchronization task is to introduce subliminal perturbations in the stimulus sequence. If such perturbations are rapidly compensated for by adjustments in the timing of the motor activity, then this would seem to provide evidence against one or the other threshold hypothesis. There are already some relevant data in the literature. Hary and Moore (1985, 1987) and Thaut et al. (1998a) used a "step" change paradigm (Michon, 1967) in which a constant stimulus period changed abruptly and then remained constant at the new value. This is a special case of the interval discrimination paradigm (*viz.*, tempo discrimination), in which the detection threshold can be as low as 2% (Drake and Botte, 1993; McAuley and Kidd, 1998). It is also the paradigm that most obviously requires period correction in the timekeeper that paces the motor activity. The step changes introduced in the studies just mentioned were below or near the detection threshold (1.4% or 2%). Nevertheless, compensation was observed. Hary and Moore (1987) and Thaut, Tian, and Azimi-Sadjadi (1998b) used stimulus sequences whose period was continuously modulated, either randomly or periodically. Although perceptual thresholds for such perturbations are not well established, the smallest changes introduced did appear to be subliminal. Again, correlational evidence for compensation was found. Thus there is already considerable evidence that the interval discrimination threshold does not limit period correction in synchronized tapping. However, there are few findings that directly contradict a role of the temporal order threshold in phase error correction.

The experiment summarized here (described in more detail as Experiment 1 in Repp, 2000) used a perturbation paradigm that has been neglected in synchronization tasks: the lengthening or shortening of a single interval in an isochronous sequence. Michon (1967) called this a "pulse" change. This local perturbation represents a phase shift in the stimulus sequence, and thus it is likely to trigger a phase correction in the synchronized motor activity, based on perception of the phase error. At the same time, it also represents a local change in the stimulus period, so that a correspondingly local adjustment of the timekeeper period pacing the response, based on perception of the change in stimulus period, cannot be ruled out a priori. The present experiment thus was relevant to both threshold hypotheses, though probably more to one than to the other.

Repp (1999) had used the same perturbation paradigm in a previous experiment in which participants tapped in synchrony with an isochronous musical sequence. He found that 20-ms increments in the duration of single intervals were immediately and perfectly compensated for in the motor response. Since the baseline interval was 500 ms, the perturbation (4%) was near both the interval discrimination and temporal order thresholds. In order to provide a more stringent test, the present experiment used pulse changes that were well below both thresholds. If such changes are nevertheless compensated for effectively, *and* if the compensation is based on perceptual information about the change in interval duration, then the results would provide clear evidence against a limiting role of the interval discrimination threshold in synchronization error correction. However, if the compensation is instead based on perception of the phase error, which seems intuitively more plausible, then the results would not immediately rule out the temporal order threshold as a factor, due to the inevitable presence of large variability in motor timing: Compensation could still be based exclusively on supraliminal phase errors because the perturbation shifts the probability distribution of phase errors at the perturbation point, making large errors in one direction more likely than in the other. Detailed data analyses were conducted to examine that possibility.

Method

The stimuli were sequences of 50 high-pitched tones with a baseline inter-onset interval (IOI) of 500 ms, played under MIDI control on a Roland RD-250s digital piano. Each sequence contained four changed IOIs, which were equal in duration and separated by exactly nine baseline IOIs. There were four increment sizes ($\Delta t = 10, 8, 6,$ and 4 ms) and four decrement sizes ($\Delta t = -10, -8, -6,$ and -4 ms), representing changes of 2%, 1.6%, 1.2%, and 0.8%, respectively. For each of these eight Δt values, there were 10 sequences (trials). The position of the first change varied. The trials were randomly arranged into 8 blocks of 10, except that IOI increments and decrements were presented in alternate blocks. Eight musically trained individuals, including the author, participated. They responded on a silent MIDI keyboard by depressing a white key in synchrony with the tones.

Results and discussion

A preliminary analysis of the data revealed that, on average, the asynchrony at the end of a trial was not significantly different from the one at the beginning, and this was true for all sizes of Δt . If there had been no compensation for perturbations, the average asynchrony should have changed by $-4\Delta t$ because there were four pulse changes in the same direction in each sequence. Thus, compensation occurred in all conditions.

To examine the time course of this motor compensation, 4 contiguous episodes of 10 tone/tap pairs each were extracted from the data of each trial, with each episode ranging from the third tone/tap preceding a perturbation (P) to the sixth tone/tap following P. Since the absolute (as expected, negative) asynchronies were not of particular interest, relative asynchronies were computed by subtracting the average of the three pre-P asynchronies from all asynchronies in an episode. For each Δt , the relative asynchronies were averaged across the 4 episodes per trial, the 10 trials, and the 8 participants.

The average "compensation functions" for the different Δt sizes are shown in Figure 1. The average relative asynchrony in position P was reasonably close to $-\Delta t$, as expected. Compensation is shown by a return of the relative asynchronies to zero following P. Such a return can be seen in all Δt conditions, generally within two or three taps. From position P+2 or P+3 on, the average relative asynchronies were generally not significantly different from zero, but they were significantly different from $-\Delta t$. (For statistical analyses, see Repp, 2000.) Nevertheless, it may be noted that the compensation functions did not cluster as tightly around zero after P as before P, which suggests a slight undercompensation, especially for the larger changes. However, this tendency has not been observed consistently in subsequent experiments (Repp, 2000).

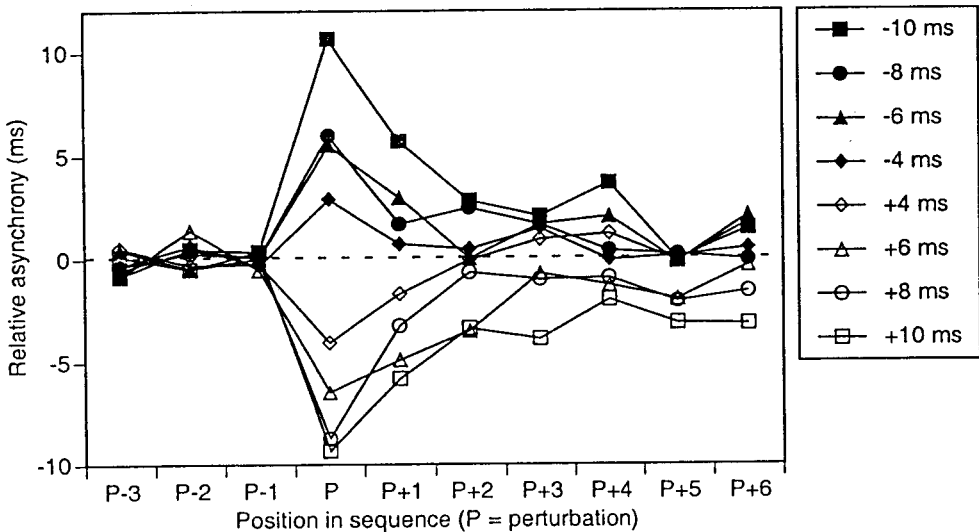


Figure 1. Average compensation functions (relative asynchrony as a function of position near a perturbation P) for various perturbation magnitudes.

The results show that perturbations well below the interval discrimination threshold are compensated for quickly and fairly effectively. The very unlikely possibility that tapping in synchrony with an auditory sequence lowers the interval discrimination threshold is ruled out by the

results of another synchronization experiment in which participants also had to report any changes they detected in the stimulus (Repp, 2000: Exp. 5). It showed the detection threshold to be in the expected region (4–5%). However, the interval discrimination threshold may be irrelevant because it is likely that the motor compensation was based on perception of phase errors only.

Asynchronies are extremely variable from tap to tap, so much so that data from single trials are impossible to interpret. Standard deviations can exceed 20 ms, so that the probability distribution of asynchronies may range over 80 ms or more. Thus there are many occasions on which an asynchrony deviates from the mean asynchrony (assumed to represent the PSS) by more than about 20 ms, the temporal-order threshold established by Hirsh and Sherrick (1961). A perturbation of magnitude Δt leads to a shift in the mean of the asynchrony distribution by $-\Delta t$, thus increasing the probability of large phase errors in one direction and decreasing their probability in the other direction. In theory, therefore, compensation for subliminal timing perturbations could derive solely from compensation for supraliminal phase errors, even though the relative rapidity of the average compensation seems to argue against the probabilistic and intermittent nature of such a process.

To address this issue more directly, the data were analyzed contingent on the actual size of the asynchrony at the point of perturbation. Each participant's data for all Δt conditions combined (320 episodes) were sorted into 10-ms bins according to the magnitude of the absolute asynchrony in position P. The asynchronies were then averaged across the episodes in each bin. For each participant, a center bin in the middle of his or her range (presumably the one closest to the PSS) was selected, the other bins were relabeled relative to the center bin, and the data of the participants were aligned according to these labels and averaged.

The results are shown in Figure 2. The graph reveals that in all bins, with the exception of the center bin, the preselected asynchrony at position P returned to its pre-P baseline level within two or three taps, even for asynchronies that were within 20 ms of the center bin, that is below the usually quoted temporal order threshold. This is consistent with the linear error correction model proposed by Vorberg and Wing (1996) and suggests that phase error correction is not limited by the temporal order threshold. An unexpected finding, however, was that the pre-P baseline covaried positively with the preselected magnitude of the asynchrony at point P. That is, large deviations from the PSS at point P were more likely when the pre-P asynchronies already deviated from the PSS in the same direction. This reveals that successive asynchronies do not vary randomly but are positively correlated. (See also Madison, this volume.)

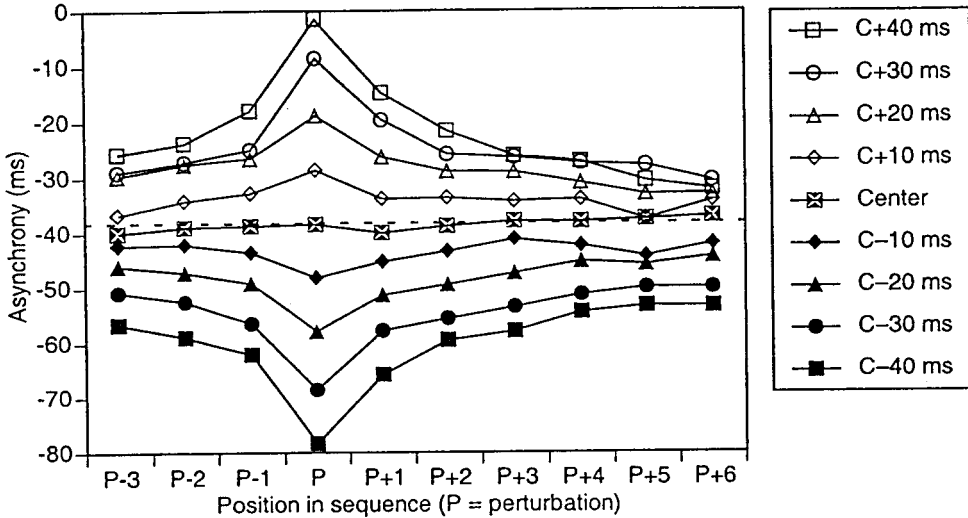


Figure 2. Average compensation functions for selected magnitudes of the absolute asynchrony in position P, grouped into 10-ms bins relative to a bin in the center of the range. Reproduced from Repp (2000) with kind permission of Springer-Verlag.

The impressionistic conclusion drawn from Figure 2 can be made more precise by plotting the difference between the average asynchronies at points P+1 and P as a function of the average asynchrony at point P. Figure 3 shows that this function is very nearly linear (with a slope of $-.35$), whereas a threshold model would predict a step function, indicated schematically by the dashed line. In other words, the asynchrony difference should be close to zero within a range of about ± 20 ms around the PSS. (This was verified in a simple computer simulation, kindly provided by Jeff Pressing, personal communication.) Note that this prediction concerns only the change in average asynchronies between points P and P+1; at point P+1, response variability will again lead to a certain proportion of suprathreshold asynchronies, so that the threshold hypothesis predicts some compensation following P+1. Note also that the foregoing analysis is quite independent of the presence of perturbations, which merely increased the range of observable asynchronies at point P. The analysis could just as well have been performed on tapping data obtained with an isochronous stimulus sequence. It is a graphic way of showing that the data are consistent with a linear error correction model.

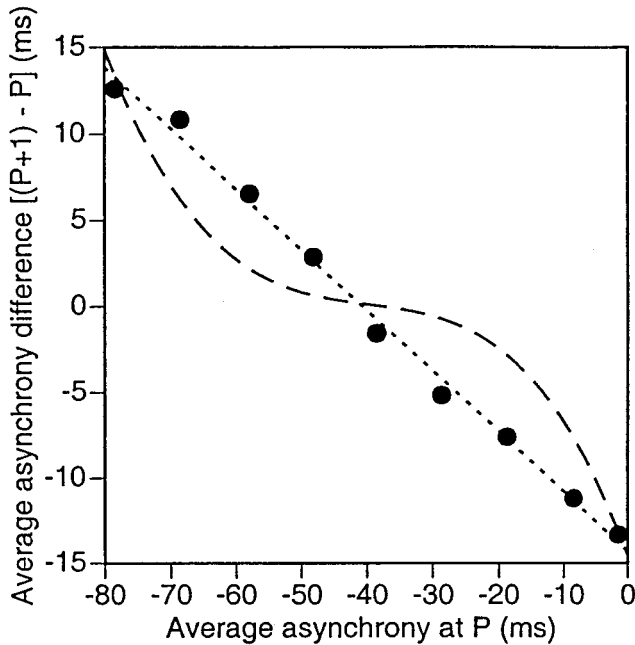


Figure 3. The change in asynchrony between points P and P+1 as a function of the asynchrony at P (data from Figure 2). The dotted line is the best linear fit; the dashed line indicates the kind of function predicted by the threshold model. Reproduced from Repp (2000) with kind permission of Springer-Verlag.

There remains one possible concern. The data on auditory-tactile temporal-order thresholds (Hirsh and Sherrick, 1961) are rather old and were obtained with tactile stimuli received passively from a vibrator, not generated actively through movement and kinesthetic feedback. Could it be that the temporal order threshold is much lower than ± 20 ms when active movement is involved? This seemed unlikely but nevertheless worthy of investigation, since the temporal order threshold had not been previously assessed in the context of a synchronization task. Experiment 2 of Repp (2000) addressed this issue. Six of the participants in Experiment 1 returned to tap silently in synchrony with short tone sequences in which the final tone was lowered by 3 semitones to signal the end of the sequence and to prevent the occurrence of an additional tap. After each trial, they judged whether their last tap had preceded or followed the last tone. The response percentages, plotted as a function of asynchrony magnitude, showed that only one participant was able to make these temporal order judgments with the degree of accuracy expected from the literature (Hirsh and Sherrick, 1961), namely with better than 75% accuracy for asynchronies outside a central range of about 40 ms (± 20 ms from the presumable PSS). Three other participants did far more poorly, and two (including the author, the most practiced participant) were totally at chance. Nevertheless, all of them

had shown compensation for subliminal perturbations in Experiment 1. Clearly, this strengthens the evidence against the threshold hypothesis, as far as the temporal order threshold is concerned. Similar conclusions were reached by Koch (1999) in a related study.

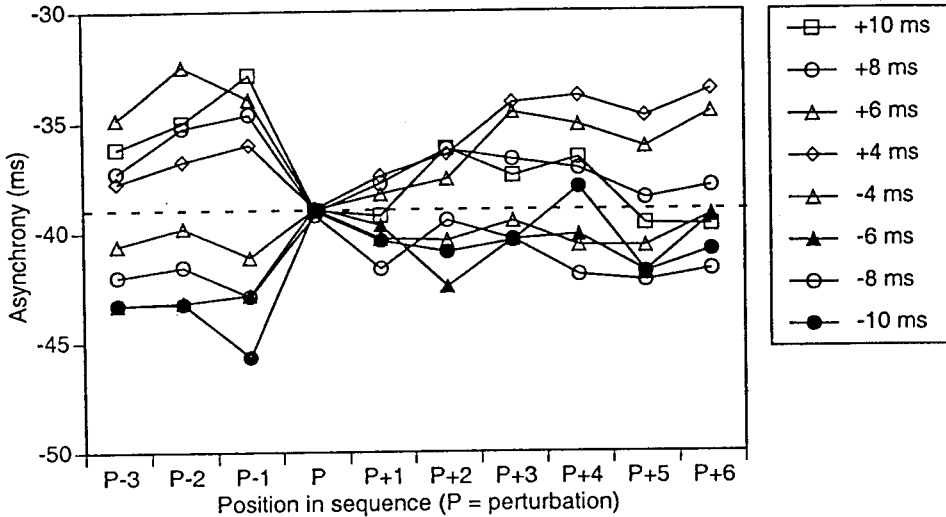


Figure 4. Average compensation functions for the different perturbation magnitudes after equalizing the average asynchronies in position P.

Do the present results also provide evidence against the other version of the threshold hypothesis, which says that the interval discrimination threshold limits period correction in synchronization? This would only be the case if it could be shown that period correction actually occurred. Another analysis of the data of Experiment 1 was conducted to address this issue. (This analysis was not reported in Repp, 2000.) It is based on the assumption that period correction, to the extent that it is a reaction to a perceived change in stimulus interval duration (an “echo” of the pulse change, as it were), should be independent of the asynchrony at point P. Thus it should occur even when the subjective phase error is zero, that is when the asynchrony is at the PSS, a situation in which no phase error correction is assumed to occur. Of course, there were only few trials for which that was actually the case, and variability was too great to draw any conclusions from such a small amount of data. Instead, all episodes were sorted according to the magnitude of the asynchrony at point P, separately for each participant and each value of Δt , and episodes were removed from one end of each array until the average asynchrony at point P closely approximated the grand mean asynchrony (the presumable PSS) of that participant. The data were then averaged over the remaining episodes for each Δt and over all participants.

The results are shown in Figure 4. The average PSS (grand average asynchrony) is indicated by the horizontal dashed line. It can be seen that

the asynchronies preceding the perturbation P tended strongly in the direction of $PSS + \Delta t$. This is a consequence of the selection procedure, which basically shifted the pre-P asynchronies up or down (cf. Fig. 1) to achieve the desired value in position P, plus some statistical regression to the mean, since in the eliminated episodes the pre-P asynchronies were likely to be less extreme than the asynchrony at point P. What is of interest here is what happened after the perturbation. Since there should not be any phase correction (on the average) when the average phase error is zero, any shift of the mean asynchrony in the direction of Δt should be due to period correction. It can be seen that there was indeed such a shift, though it was not very orderly.

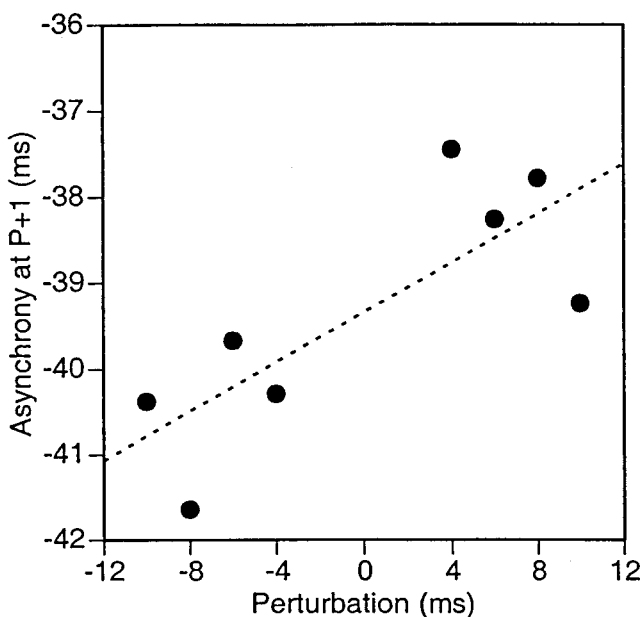


Figure 5. The asynchrony at point P+1 as a function of perturbation magnitude (data from Fig. 4). The dotted line is the best linear fit.

Figure 5 plots the mean asynchronies at point P+1 as a function of the perturbation magnitude Δt . The dotted line represents the best linear fit, which has a slope of .14, less than half that of the linear function in Figure 3. While this could indeed represent a small period correction (which would be consistent with the coupled oscillator model of Large and Jones, 1999), the trend is exclusively due to the difference between positive and negative Δt conditions; there is no systematic ordering of data points within each of these conditions, and this is also true at positions following P+1 (see Fig. 4). An alternative explanation of these data might be that the PSS was not constant throughout the experiment but varied somewhat between the

various Δt conditions—in other words, that the pre-P asynchronies were more representative of the PSS than the grand mean asynchrony. In that case, the trends observed in Figures 4 and 5 would represent phase error correction, after all. Thus, this analysis remains inconclusive with regard to the occurrence of period correction.

Repp (2000) reports three additional experiments which demonstrate that stimulus factors that affect the detection threshold for perturbations in stimulus timing leave the motor compensation for such perturbations unaffected. These experiments provide further evidence for a dissociation of conscious perception from the direct use of temporal information for the control of action.

Conclusions

The present results refute the threshold hypothesis often stated in the tapping literature, namely that the perceptual temporal order threshold limits phase error correction in synchronization. While they do not bear on the hypothesis that the interval discrimination threshold limits period correction in synchronization, that other threshold hypothesis is already contradicted by other findings (Hary and Moore, 1985, 1987; Thaut et al., 1998a, 1998b). The results seem in agreement with the linear phase error correction model of Vorberg and Wing (1996) and its elaborations by Semjen et al. (1998) and Pressing (1998), although it remains to be seen whether these models can account fully for the data shown in Figures 2 and 4.

The general conclusion is that the temporal information available to the timekeeping and feedback mechanisms in sensorimotor coordination is different from the one that enables a listener to explicitly detect deviations from temporal regularity or judge the temporal order of two events. There appears to be a level of highly accurate temporal perception subserving motor control, which precedes the level of conscious perception and judgment (see also Thaut et al., 1998a, 1998b). At that later stage, temporal information seems to be fraught with a significant amount of perceptual noise that is responsible for the psychophysical thresholds. Automatic error correction in perceptual-motor synchronization thus constitutes an instance of what has been variously called perception-action coupling (Kelso and Kay, 1987), direct parameter specification (Neumann, 1990), or entrainment (Thaut et al., 1998b; Large and Jones, 1999). The results are also pertinent to recent research on the diverse brain structures subserving conscious timing perception and timing control in action (see, e.g., Rao et al., 1997; Harrington, Haaland and Hermanowicz, 1998; Harrington, Haaland and Knight, 1998).

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