

Bruno H. Repp

Multiple temporal references in sensorimotor synchronization with metrical auditory sequences

Received: 9 September 2005 / Accepted: 19 April 2006 / Published online: 25 May 2006
© Springer-Verlag 2006

Abstract A local phase perturbation in an auditory sequence during synchronized finger tapping elicits an automatic phase correction response (PCR). The stimulus for the PCR is usually considered to be the most recent tap-tone asynchrony. In this study, participants tapped on target tones (“beats”) of isochronous tone sequences consisting of beats and subdivisions (1:*n* tapping). A phase perturbation was introduced either on a beat or on a subdivision. Both types of perturbation elicited a PCR, even though there was no asynchrony associated with a subdivision. Moreover, the PCR to a perturbed beat was smaller when an unperturbed subdivision followed than when there was no subdivision. The relative size of the PCRs to perturbed beats and subdivisions depended on tempo, on whether the subdivision was local or present throughout the sequence, and on whether or not participants engaged in mental subdivision, but not on whether or not taps were made on the subdivision level. The results show that phase correction in synchronization depends not merely on asynchronies but on perceptual monitoring of multiple temporal references within a metrical hierarchy.

Introduction

Metrical structure and synchronization

Finger tapping in synchrony with an auditory tone sequence has been studied from several theoretical and methodological perspectives. Some researchers have focused on the common finding that the taps tend to precede the tones and have manipulated variables such

as sequence tempo or the nature of perceptual feedback in order to reveal the origin of the anticipation tendency (Aschersleben & Prinz, 1995, 1997; Aschersleben, Stenneken, Cole, & Prinz, 2002; Engström, Kelso, & Holroyd, 1996; Fraise, Oléron, & Paillard, 1958; Mates, Radil, Müller, & Pöppel, 1994; Wohlschläger & Koch, 2000). Others have investigated the error correction processes (phase and period correction) that are believed to underlie the ability to stay in synchrony, either by statistical modeling of raw data (Hary & Moore, 1985, 1987; Mates, 1994a, 1994b; Pressing, 1998; Schulze, 1992; Semjen, Schulze, & Vorberg, 2000; Vorberg & Schulze, 2002; Vorberg & Wing, 1996) or by examining the behavioral responses to perturbations in a sequence (Repp, 2000, 2001a, 2001b, 2002a; Thaut, Miller, & Schauer, 1998; Thaut, Tian, & Azimi-Sadjadi, 1998). Yet others have taken a dynamic systems approach to investigate instabilities of coordination as a function of changes in tempo (Engström et al., 1996; Kelso, Del-Colle, & Schöner, 1990) or to characterize the nature of the observed timing variability (Chen, Ding, & Kelso, 1997, 2001; Chen, Repp, & Patel, 2002; Pressing & Jolley-Rogers, 1997). For a review, see Repp (2005). Most of these studies have used sequences composed of identical tones or clicks whose timing was isochronous or exhibited only small deviations from isochrony, and which required one tap for each tone (1:1 in-phase synchronization, see Fig. 1a). Thus, as long as the tempo was not very fast, both the sequences and the coordinated motor behavior had the simplest possible metrical structure, which is a succession of beats.

When the tempo is fast, isochronous sequences of identical sounds can give rise to subjective perceptual grouping of the sounds into twos, threes, or fours, a phenomenon called subjective rhythmicization (Bolton, 1894; Parncutt, 1994). A corresponding phenomenon of emergent grouping in the kinematics of self-paced finger tapping at fast rates has been described by Nagasaki (1987a, 1987b). Such grouping creates a two-level metrical structure because it implies that a periodic (typically group-initial) beat is imposed mentally on the

B. H. Repp
Haskins Laboratories, 300 Crown Street,
New Haven, CT 06511-6624, USA
E-mail: repp@haskins.yale.edu
Tel.: +1-203-8656163
Fax: +1-203-8658963

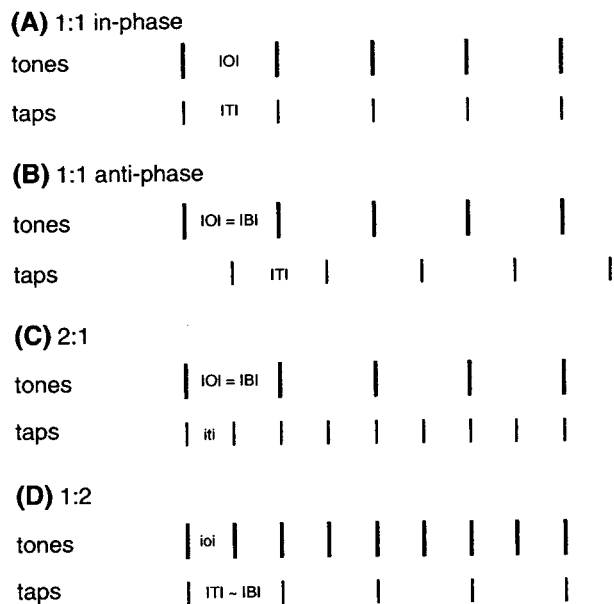


Fig. 1 Some possible modes of coordination between taps and tones in synchronization experiments. *IOI* tone inter-onset interval; *ITI* inter-tap interval; *IBI* inter-beat interval; *ioi* subdivision IOI; *iti* subdivision ITI

sequence events; perhaps “subjective metricization” would be a better name for the phenomenon. Metrical structure has received little attention in research on 1:1 sensorimotor synchronization because the sequence tempi in these experiments are usually too slow to encourage formation of a two-level hierarchy. A beat is most salient when it occurs with inter-onset intervals (IOIs) of 500–700 ms (Parncutt, 1994), and because the IOIs of sequences in synchronization studies are often in this range, each auditory event functions as a beat and each IOI is also an inter-beat interval (IBI). Moreover, the activity of making a tap to every sequence event reinforces the coincidence of the beat with each of the sequence events.

Some studies (Chen et al., 2001; Keller & Repp, 2004; Kelso et al., 1990; Pressing, 1998; Repp, 2001a, 2002a; Semjen, Schulze, & Vorberg, 1992; Vos & Helsen, 1992) have investigated syncopated (off-beat, anti-phase) 1:1 synchronization (see Fig. 1b). In that task the taps bisect the sequence IOIs and thereby create a two-level metrical structure in which the sequence events represent beats and the taps represent subdivisions. (Alternatively, but less naturally, the taps might be thought of as the beats and the sequence events as the subdivisions.) Because of the alternation of tones and taps, this binary metrical organization is likely to be maintained even when the sequence IOIs (the IBIs) fall outside the range of maximal beat salience. That a metrical level below the beat is present in anti-phase tapping is suggested by the finding that tapping variability tends to be smaller than in in-phase tapping, as long as the subdivision IOI is not shorter than about 250 ms (Semjen et al., 1992).

If participants are required to tap at a rate that is an integral multiple of the sequence rate (2:1 or n :1 synchronization, see Fig. 1c), the sequence of taps will tend to be conceived as a two-level metrical structure in which the taps coinciding with tones (as well as the tones themselves) function as beats and the other taps represent subdivisions. Vorberg and Hambuch (1978) studied this task, although their analysis focused on continuation tapping during which no explicit beat was provided. They found that the inter-tap intervals (ITIs) exhibited recurring timing patterns that reflected the period of the beat induced by a preceding n :1 synchronization task. This provided objective evidence of a persisting hierarchical metrical organization of the taps. Statistical modeling of the data, however, suggested that the ITIs were controlled in a sequential rather than hierarchical manner. The likely reason for this finding is that variability increases with interval duration (Collyer, Boatright-Horowitz, & Hooper, 1997; Peters, 1989); therefore, the most accurate timing is achieved by controlling only the ITIs between successive taps, and not also the longer IBIs. Vorberg and Hambuch (1984) later did find evidence for hierarchical timing control, at the cost of overall accuracy, in the tapping of more complex (non-isochronous) rhythms. (See also Vorberg & Wing, 1996.) Other studies that have investigated n :1 tapping include Pressing (1998) and Semjen et al. (1992).

Another way of adding structure to the synchronization task is to impose an explicit metrical structure on the auditory sequence by accenting tones periodically. Periodicities in asynchronies and ITIs have been observed in 1:1 synchronization with sequences containing a regularly recurring event of longer duration (Franěk, Radil, & Indra, 1990) or of different pitch (Franěk et al., 1991), although there were large individual differences in the observed timing patterns. Keller and Repp (2005) found clear periodicities in 1:1 anti-phase tapping with sequences containing regular combined intensity and pitch accents. Quasi-periodic timing patterns also occur in taps that are synchronized with complex piano music, and these patterns seem to reflect the metrical structure of the music (Repp, 1999a, 1999b, 1999c).

Finally, metrical structure can arise from 1:2 or 1: n tapping (see Fig. 1d), where a tap coincides with every n th event of an isochronous sequence. In that case, the taps will tend to impose a two-level metrical structure on the tone sequence, such that the tones coinciding with taps (as well as the taps themselves) function as beats and the intervening tones are perceived as subdividing the IBIs. This task is theoretically interesting for at least two reasons. First, it can be used to reveal the temporal limit of metrical subdivision. Repp (2003) compared 1:1 and 1: n tapping by keeping the tapping rate (and the IBIs) constant and varying the sequence rate (i.e., the number of subdivisions). Subdivision of the IBIs reduced the variability of tap-tone asynchronies, but only as long as the subdivision IOIs exceeded 200–250 ms (see also Semjen et al., 1992). This finding suggested that shorter subdivisions could no longer function as a level

in a metrical hierarchy, perhaps because of a rate limit of an internal timekeeper or oscillator that is entrained to the subdivision level. The second theoretical issue was the focus of the present study and is discussed in the next section.

Phase correction and metrical subdivision

Phase correction is the primary error correction process that maintains synchrony in a tapping task when the pacing sequence is isochronous or nearly so. It is usually assumed that phase correction is based on perceptual information about tap-tone asynchronies (e.g., Aschersleben, 2002; Repp, 2002c; Vorberg & Schulze, 2002). An alternative conception is that phase resetting occurs with respect to both the preceding tap and the preceding tone (Hary & Moore, 1985, 1987; Repp, 2002c). Both of these theories were developed in the context of 1:1 synchronization, where they are formally equivalent (Schulze, 1992; see also Repp, 2005). However, they make different predictions about the possible role of metrical subdivision in phase correction. In particular, the asynchrony-based theory implies that subdivision tones are irrelevant, and that phase correction should be based exclusively on beat-level asynchronies in 1:*n* tapping. This prediction constituted the null hypothesis in the present study. The phase resetting hypothesis makes the same prediction if the most recent beat tone is taken to be the sole external reference for phase resetting. If instead the most recent tone (i.e., a subdivision) is considered to serve as the sole external reference, then the phase resetting hypothesis makes the contrasting prediction that phase correction is governed entirely by the subdivision level of the sequence (if there are subdivisions).

These hypotheses are probably too simplistic. A more interesting possibility is that both beats and subdivisions can serve as external references in phase correction. This idea seems incompatible with an asynchrony-based theory because subdivisions are not associated with asynchronies in 1:*n* tapping, but it constitutes merely an elaboration of the phase resetting theory. The added assumption is that there can be more than one external reference in phase resetting. That assumption is naturally made in dynamic systems models of temporal entrainment based on weakly coupled nonlinear oscillators (Eck, 2002; Large, 2000, 2001; Large & Kolen, 1994; Large & Jones, 1999; Large & Palmer, 2002; McAuley & Jones, 2003). It is intuitively obvious that an isochronous pacing sequence will entrain not only an internal oscillator at the event frequency (1000/IOI) but also (within definite limits) oscillators at integer fractions of that frequency (1000/(2 × IOI), 1000/(3 × IOI),...), one of which may function as the main beat frequency, and/or at integer multiples (2000/IOI, 3000/IOI, ...). These multiple oscillators then constitute a dynamic internal representation of metrical structure, and any temporal perturbation of the external sequence will lead to an adaptive response of the entire system.

The hypothesis that multiple levels in a hierarchical metrical structure can contribute to error correction in synchronization has already received empirical support in an experiment conducted by Large, Fink, and Kelso (2002). Their sequences consisted of random concatenations of 1,600-ms building blocks that always began with a beat but differed in the number (0–3) and phase (0.25, 0.50, 0.75 of the IBI) of subdivisions.¹ Thus the sequences had three metrical levels, and participants were asked to tap at each of the three levels, in different conditions. Two types of timing perturbation, phase shifts and step (tempo) changes, were introduced at various points in the sequence, and participants' reactions to these perturbations were examined. The results showed responses to perturbations at each metrical level, even when other tones intervened between the perturbed tone and the next tap. Large et al. (2002) concluded that "synchronization need not always be based on a perceived asynchrony between a physical tap and a physical stimulus event" (p. 15) and that "synchronization at each tapping level reflects information from other metrical levels" (p. 3).

Because Large et al. (2002) introduced both phase and period perturbations in their sequences, it is conceivable that both phase and period correction mechanisms were engaged in their study. Experiment 1 of the present study (carried out independently at about the same time; cf. Repp, 2002b) had essentially the same goal as their research but employed only phase perturbations and less complex sequences, so that the investigation was restricted to phase correction. Experiment 1 also investigated the role of (unperturbed) sequence tempo, which was not varied by Large et al. (2002). Experiment 2 was a replication with a slight change in procedure. Experiments 3, 4, 5 and 6 used variants of the same paradigm to investigate variables that may affect the relative salience of metrical levels, reflected in phase correction elicited by perturbations.

The event onset shift paradigm

Whereas Large et al. (2002) had used permanent phase shifts to perturb phase (i.e., all tones from a certain point on were phase-shifted), the present experiments used the local phase shift or *event onset shift* (EOS) paradigm (Repp, 2002a). Previous research on 1:1 synchronization has shown that, when a single tone in an isochronous sequence is made to occur earlier or later than expected, participants automatically shift their next tap in the same direction, even when they are instructed not to react to the EOS. This involuntary shift was

¹Large et al. (2002) call the events at the lowest metrical level (IOI = 400 ms) beats and thus do not talk about subdivisions. However, the perceived main beat (tactus) was probably either at the 1,600-ms level (because of the modular structure of the sequences) or at the 800-ms level (because at this rate the beat salience is maximal), so that the events at the lowest level functioned as subdivisions.

termed the *phase correction response* (PCR). Repp (2002a, 2002d) found that the PCR increases linearly with EOS magnitude up to a certain point but then reaches an asymptote. For EOSs smaller than about 15% of the IOI, the mean PCR amounted to about 30% of the EOS, although there were considerable individual differences. A much larger PCR, almost as large as the EOS itself, was observed when the tap that would have coincided with the shifted tone was withheld. In other words, almost complete phase resetting with reference to the perturbed tone occurred in the absence of a preceding tap. This *phase resetting paradigm* was employed in Experiment 1 in order to magnify the behavioral effects of small EOSs in the sequences. Subsequent experiments, however, used the standard EOS paradigm (i.e., without an omitted tap).

The pacing sequences consisted of beats and subdivisions, and an EOS could be introduced either on the beat (by shifting a beat tone) or off the beat (by shifting a subdivision tone). Beats were defined as the tones that coincide with taps in 1:*n* tapping (Fig. 1d). The two crucial questions then were: (1) Do one or more unperturbed subdivisions following a shifted beat reduce the PCR to the EOS, compared to a baseline condition in which there are no subdivisions? (2) Does a shifted subdivision tone following an unperturbed beat elicit a PCR? According to an asynchrony-based theory of phase correction, the PCR to a shifted beat should not be affected by any intervening subdivisions, and shifted subdivisions should not elicit a PCR. According to a theory of phase resetting based on the most recent tone, the PCR to a shifted beat should disappear completely when the beat is followed by one or more unperturbed subdivisions, and a shifted subdivision tone should elicit a PCR, provided that it is not followed by yet another subdivision tone that is unperturbed. If both levels in the metrical hierarchy serve as external references, however, then unperturbed subdivisions should reduce but not eliminate the PCR to a shifted beat, and shifted subdivisions should also elicit a PCR, at least when they immediately precede the critical tap.

Two experiments reported in Repp (2002a) used the EOS paradigm to test these hypotheses for the case of 1:2 tapping at a single tempo. At the time, however, these results were not presented as concerning metrical structure; rather, the subdivision tones were regarded as a distractor sequence that was interleaved with a target sequence. Nevertheless, it was found that an unperturbed distractor tone reduced the PCR to a beat-level EOS by about 50%, and that a perturbation of a distractor tone elicited a PCR of about the same size. These experiments can be seen as forerunners of the present study, which extends them in several ways.

Experiment 1

Experiment 1 employed three types of subdivision: duple (i.e., one subdivision tone, as in Fig. 1d), triple (two

subdivision tones), and quadruple (three subdivision tones). The latter conditions made it possible to examine (1) whether the PCR (if any) to a perturbed subdivision tone is inhibited by a following unperturbed subdivision tone, (2) whether shifting several subdivision tones as a unit results in a larger PCR than if only the last tone is shifted, and (3) whether the second subdivision tone in quadruple subdivision elicits a PCR even when it is followed by an unperturbed tone, because it constitutes an intermediate level in a three-level ($2 \times 2 \times 2$) metrical structure.

In addition, the experiment presented sequences at two beat tempi (IBIs). It is well known that increasing the tempo of a rhythm can move the perceived main beat (tactus) to a higher metrical level (e.g., Parncutt, 1994). Even if no such categorical shift occurs (and none was expected here because the taps basically defined the beat level), it was expected that the beat level would be strengthened and the subdivision level would be weakened by an increase in tempo. This tempo-conditioned change in relative salience of metrical levels, which may reflect a preferred resonance frequency of the human body (Todd, Lee, & O'Boyle, 2002; van Noorden & Moelants, 1999), should be reflected in a change in the relative magnitude of the PCRs to beat-level and subdivision-level EOSs.

Methods

Participants

Eight paid volunteers (4 women, 4 men) and the author participated. All had good rhythmic skills and were regular participants in synchronization experiments. Ages ranged from 18 to 57, and musical training ranged from professional level (1 participant) to none at all (1 participant). All participants were right-handed and tapped with the right hand.

Materials

There were 11 different conditions, the critical episodes of which are depicted schematically in Fig. 2. Each row shows two beat-level tones (thick bars), the first of which (beat 10) preceded the critical tap, whereas the second one (beat 11) coincided approximately with the critical tap. The critical tap was the one on which the PCR was measured (see bottom of figure). Between the two critical beats, there were 0–3 subdivision tones (thin bars), depending on the condition. Arrows symbolize shifts of tones (EOS) or taps (PCR). In the names given to the conditions, the initial digit indicates the subdivision condition (duple, triple, quadruple), the following letter indicates the metrical level on which the EOS is located (*s* = strong, or beat level; *w* = weak, or subdivision level), and the final digits indicate the subdivisions on which EOSs are located (“12” is to be read as “both one

| Condition | Beat 10 | Subdivisions | Beat 11 |
|-----------------|---------|--------------|------------|
| 1s | ◀+▶ | | |
| 2s | ◀+▶ | | |
| 2w | | ◀+▶ | |
| 3s | ◀+▶ | | |
| 3w1 | | ◀+▶ | |
| 3w2 | | | ◀+▶ |
| 3w12 | | ◀+▶ | ◀+▶ |
| 4s | ◀+▶ | | |
| 4w2 | | | ◀+▶ |
| 4w3 | | | |
| 4w123 | | ◀+▶ | ◀+▶ |
| Exp. 1 (no tap) | | | PCR ◀+▶ |
| Exp. 2 | | | ◀+▶ |

Fig. 2 Schematic illustration of the different conditions in Experiments 1 and 2. Only the critical episode of the sequences is shown (between beats 10 and 11). *Thick bars* represent beats (or, in the bottom two rows, taps), and *thin bars* represent subdivisions. *EOS* event onset shift (symbolized by *arrows with unfilled heads*); *PCR* phase correction response (symbolized by *arrows with filled heads*)

and two”). For reasons of economy, only four of the eight possible EOS conditions with quadruple subdivision were included. In the two conditions in which more than one EOS occurred (3w12, 4w123), all subdivision tones were shifted as a group.

Each sequence contained 15 beat-level tones. Subdivisions, if any, began after the second beat; the first IBI was always empty. The IBI duration was either 540 ms (fast tempo) or 720 ms (slow tempo). All sequences consisted of high-pitched digital piano tones. Beat-level tones had a musical pitch of B-flat₇ (3,729 Hz), subdivision tones a pitch of A₇ (3,520 Hz). The three beat-level tones located in positions 7, 8, and 9 had a pitch of A-flat₇ (3,322 Hz). These tones served as a cue to withhold the tap in position 10. Thus, beat-level tones were one semitone higher than subdivision tones, whereas cue tones were one semitone lower than subdivision tones and one whole tone lower than other beat-level tones. These pitch separations were deliberately kept small in order to prevent perceptual segregation (auditory streaming) of beat and subdivision tones. The temporary reversal of the pitch relationship between beat-level and subdivision tones helped make the cue tones salient.

The EOS always occurred in position 10, either on the beat or on one or more of the following subdivi-

sions (see Fig. 2). The EOS magnitudes were -60 ms (advance) and $+60$ ms (delay). These perturbations were easily detectable because they constituted 8.3% to 44.4% of the IOI duration, depending on the condition, whereas the average detection threshold for an EOS is about 4% of the IOI (Friberg & Sundberg, 1995; Repp, 2002a). In addition to the sequences containing EOSs, completely isochronous sequences representing each of the four types of subdivision were included as a baseline. Thus, there were 11 (EOS conditions) \times 4 (EOS magnitudes)² + 4 (isochronous baseline sequences) = 48 sequences at each of the two beat tempi. Six random orders of these sequences were created at each tempo, and each of these blocks was divided into two halves.

Equipment and procedure

Sequence presentation and recording of finger taps was controlled by a program written in MAX 3.0, which ran on a Macintosh Quadra 660AV computer.³ The sequences were played back on a Roland RD250s digital piano according to musical-instrument-digital-interface (MIDI) instructions (prepared off-line) which specified key depression times, key release times, pitches, and key velocities. All tones had sharp onsets and a nominal duration of 20 ms. (Some decay followed the nominal offset.) Beat-level tones had a MIDI key depression velocity of 60, whereas subdivision tones had a velocity of 50, which amounts to a difference of about 3 dB (Repp, 1997: Fig. 1). This difference was introduced to facilitate synchronization with the beat.

Participants sat in front of a computer monitor on which the current trial number was displayed and listened to the sequences over Sennheiser HD540 II earphones at a comfortable intensity. They tapped on a Fatar Studio 37 MIDI controller (a quiet three-octave piano keyboard) by depressing a white key with the index finger of the preferred hand in synchrony with the beat-level tones. The MIDI controller was held on the lap, and participants were asked to keep their finger in contact with the response key, which moved vertically by about 1 cm. The key had a cushioned bottom contact and did not produce any audible sound unless it was struck rather hard (as may have been the case with some participants).

Participants were instructed to start tapping with the second tone in each sequence and to stay with the beat. Any temporal irregularities in the sequences (i.e., the EOSs) were to be ignored. Participants were also told that, after hearing three successive beat-level tones at a

²The experiment also contained sequences with much smaller, mostly subliminal EOSs (± 10 ms). The results, while generally consistent with those for the larger EOSs, were too variable to reach statistical significance and therefore are not reported.

³All intervals are reported here as specified or recorded by the MAX software. It is known from acoustic measurements that the real-time temporal intervals generated or recorded by MAX in this configuration were shorter by about 2.4%.

lower pitch, they should omit the following tap by holding the finger still on the response key and resume tapping on the next beat. The interval between sequences in a block was 4 s.

Participants came for three 1-h sessions, typically 1 week apart. Blocks representing the different beat tempi were presented in alternation, with some participants starting with the faster tempo and others with the slower one. Two blocks at each tempo were presented during each session.

Analysis

The raw data (tap-tone asynchronies) were edited to eliminate trials in which participants had forgotten to omit one tap, had omitted it at the wrong time, or had produced grossly anomalous asynchronies for some other reason (which was rare). These deleted trials amounted to 4.6% of the data (1.4–9.2% for individual participants). The asynchronies were averaged across the six (or fewer) exact replications of each sequence. Then the mean PCR in each condition was calculated by subtracting the mean asynchrony of the tap in position 11 of the pertinent isochronous baseline sequence from that of the critical tap (also in position 11) in the sequence containing the EOS. In order to avoid trivial effects of EOS direction, the signs of the (typically negative) PCRs to negative EOSs were reversed before submitting the data to repeated-measures ANOVAs. The variables in the ANOVAs were EOS direction (negative, positive), condition (depending on the analysis), and beat tempo (fast, slow). For effects involving variables with more than two degrees of freedom, the Greenhouse-Geisser correction was applied, and the value of ϵ is reported.

For graphic presentation, the results were condensed further by expressing each PCR as a percentage of EOS magnitude and by averaging these percentages across positive and negative EOSs. These measures were then averaged across participants, and standard errors were calculated. The results are presented as bar graphs with double standard errors. A significant PCR is one whose standard error bars do not include zero.⁴

Results

Figure 3a shows the PCR results for the four conditions in which the EOS was located on the beat (1s, 2s, 3s, 4s; see Fig. 2). These data are relevant to the question of whether intervening subdivision tones reduce or perhaps completely eliminate the response to a beat-level EOS. It can be seen that, in the absence of subdivision tones

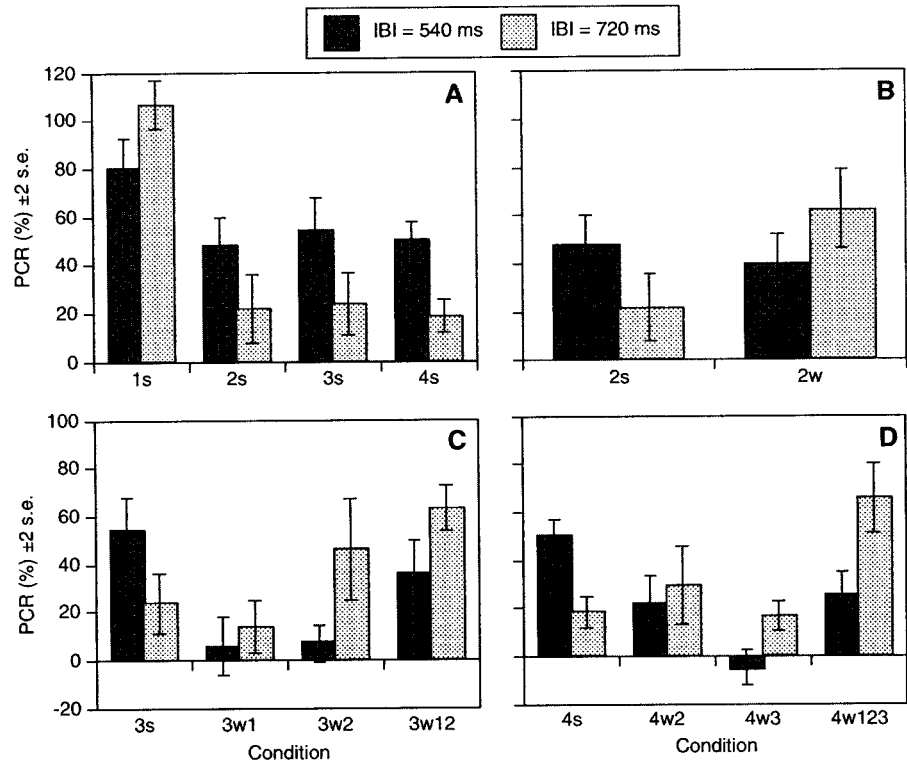
(condition 1s), there was complete phase resetting (i.e., a PCR close to 100%) at the slow tempo and about 80% at the fast tempo. When subdivision tones intervened, the PCR was reduced but not eliminated. As predicted, the reduction was much stronger at the slow tempo (which strengthened the relative salience of the subdivision level) than at the fast tempo (which strengthened the relative salience of the beat level). Interestingly, the number of subdivision tones did not make any difference. In the ANOVA, the main effect of condition, $F(3,24) = 58$, $P < 0.0001$, $\epsilon = 0.73$, and the Condition \times Tempo interaction, $F(3,24) = 13.5$, $P < 0.0001$, $\epsilon = 0.77$, were highly reliable. The main effect of tempo was also significant, $F(1,8) = 32.4$, $P < 0.001$. No effects involving EOS direction reached significance. When the 1s condition was omitted from the ANOVA, the condition main effect and the interaction disappeared; only the main effect of tempo remained, $F(1,8) = 104.1$, $P < 0.0001$. In addition, however, a significant Tempo \times Direction interaction emerged, $F(1,8) = 8.7$, $P < 0.02$: At the fast tempo, the PCR to a positive EOS was larger than that to a negative EOS, but at the slow tempo, the opposite was true. (This result cannot be seen in Fig. 3a.)

Figure 3b compares the results for the duple subdivision conditions (2s and 2w; see Fig. 2). A significant PCR was present in the 2w condition, contrary to the asynchrony-based theory. Whereas the PCR to a beat-level EOS (2s) was larger at the fast than at the slow tempo, the PCR to a subdivision-level EOS (2w) showed the opposite pattern, as predicted. The Condition \times Tempo interaction was highly reliable, $F(1,8) = 46.2$, $P < 0.0002$. The main effect of condition also reached significance, $F(1,8) = 5.6$, $P < 0.05$, but has little meaning in view of the interaction with tempo. No effects involving EOS direction reached significance.

Figure 3c presents the results for the sequences with triple subdivision (3s, 3w1, 3w2, 3w12; see Fig. 2). The data show an interaction similar to that seen in Fig. 3b: Whereas the PCR to a beat-level EOS (condition 3s) was larger at the fast than at the slow tempo, the reverse was true when the EOS was located on the lower metrical level. The Tempo \times Condition interaction was highly reliable, $F(3,24) = 12.5$, $P < 0.0001$, $\epsilon = 0.73$, as was the less interesting main effect of condition, $F(1,8) = 12.8$, $P < 0.0001$. Two other effects reached significance: the main effect of tempo, $F(1,8) = 9.0$, $P < 0.02$, and the Condition \times Direction interaction, $F(3,24) = 3.7$, $P < 0.05$, $\epsilon = 0.73$. The interaction reflected larger PCRs to positive than to negative EOSs in the subdivision-level EOS conditions, but not in the beat-level EOS condition. In a separate ANOVA on the three subdivision-level EOS conditions alone, however, the main effect of EOS direction was not significant. In that analysis, the main effects of tempo, $F(1,8) = 35.2$, $P < 0.0004$, and of condition, $F(2,16) = 28.1$, $P < 0.0001$, $\epsilon = 0.89$, were reliable, whereas the Condition \times Tempo interaction fell just short of significance,

⁴Double standard errors are slightly smaller than two-tailed but slightly larger than one-tailed 95% confidence intervals. A one-tailed test against zero is justified here because mean PCRs are expected to be in the same direction as the EOS.

Fig. 3 Results of Experiment 1, with double standard errors. *IBI* inter-beat interval; *PCR* phase correction response



$F(2,16) = 3.7$, $P < 0.06$, $\varepsilon = 0.93$. A shift of the first subdivision tone (3w1) generally had little effect, a shift of the second subdivision tone (3w2) had a much larger effect at the slow than at the fast tempo, and a shift of both subdivision tones (3w12) had large effects at both tempi, but a larger effect at the slow than at the fast tempo.

Finally, Fig. 3d shows the results for the quadruple subdivision conditions (4s, 4w2, 4w3, 4w123; see Fig. 2). PCRs to beat-level EOSs (4s condition) were again larger at the fast than at the slow tempo, whereas the opposite was true for PCRs to subdivision-level EOSs (4w2, 4w3, 4w123). This Tempo \times Condition interaction was highly reliable, $F(3,24) = 23.1$, $P < 0.0001$, $\varepsilon = 0.70$, as was the main effect of condition, $F(3,24) = 19.7$, $P < 0.0001$, $\varepsilon = 0.63$. In addition, the Condition \times Direction interaction was significant, $F(3,24) = 6.2$, $P < 0.01$, $\varepsilon = 0.76$: Beat-level PCRs were larger to negative than to positive beat-level EOSs, but the reverse was true for PCRs to subdivision-level EOSs. A separate ANOVA on the three subdivision-level EOS conditions still showed a significant difference between conditions, $F(2,16) = 26.7$, $P < 0.0001$, as well as a significant main effect of tempo, $F(1,8) = 13.6$, $P < 0.01$, a Tempo \times Condition interaction, $F(2,16) = 8.9$, $P < 0.01$, $\varepsilon = 0.70$, and a Condition \times Direction interaction, $F(2,16) = 6.3$, $P < 0.02$, $\varepsilon = 0.93$. The PCRs were smaller in the 4w3 condition than in the 4w2 condition, which in turn were smaller than those in the 4w123 condition. Tempo had a greater effect in the 4w123 condition than in the 4w2 and 4w3 conditions. Moreover, PCRs were much larger for

positive than for negative EOSs in the 4w2 condition (there was virtually no PCR to negative EOSs), whereas there was no effect of EOS direction in the other two conditions. (This last result cannot be seen in Fig. 3d.)

Discussion

The results of Experiment 1 provide clear evidence that a two-level hierarchical representation of metrical sequence can play a functional role in sensorimotor synchronization. Thus the results confirm the previous findings of Large et al. (2002) and Repp (2002a). If only the beat level had been represented or attended to, as the asynchrony-based theory predicts, then the PCR to a beat-level EOS should not have been affected by intervening subdivision tones, and no PCR should have occurred to a subdivision-level EOS. However, beat-level PCRs were substantially reduced when unperturbed subdivision tones intervened, and significant PCRs did occur to subdivision-level EOSs. Conversely, if only the subdivision level (if present) had been represented or attended to, as a simple phase resetting theory might predict, then only an EOS on the most recent tone should have elicited a PCR. This was not the case: An EOS on the more distant beat-level tone, and sometimes even an EOS on a more distant subdivision-level tone, elicited a significant PCR. Thus, both single-level timing hypotheses can be rejected, and the hypothesis that all levels of a metrical hierarchy play a role in synchronization and phase error correction is supported.

Even though the PCR did not depend solely on the timing of the temporally closest sequence event, temporal proximity of the relevant sequence events to the critical tap did play a role. The PCR to a beat-level EOS in the absence of intervening subdivision tones (condition 1s) was larger at the slow than at the fast tempo. This is consistent with evidence that phase correction in synchronization is more effective at slower tempi (Pressing, 1999; Semjen, Schulze, & Vorberg, 2000). Because sensorimotor synchronization is a form of perception-action coupling (Byblow, Chua, & Goodman, 1995; Kelso, DelColle, & Schöner, 1990; Wimmers, Beek, & van Wieringen, 1992), the finding is also consistent with the observed increase in coupling strength between limbs in motor coordination tasks (or between coupled oscillators generally) as the movement frequency decreases (see, e.g., Peper, Beek, & van Wieringen, 1995; Peper & Beek, 1998). However, this effect was reversed as soon as any subdivision tones intervened between beats. In other words, unperturbed subdivision tones reduced the beat-level PCR much more at the slow than at the fast tempo. This, too, can be seen as being consistent with the notion of frequency-dependent coupling strength because it shows that, at the slower tempo, the timing control system was more sensitive not only to the beat but even more so to the intervening subdivisions. From the perspective of metrical structure, the subdivision level increased in relative salience at the slow tempo because its frequency was closer to the region of possible or preferred beat frequencies (Parncutt, 1994; van Noorden & Moelants, 1999).

Interestingly, the PRC to a beat-level EOS did not vary as a function of the number of intervening tones (1, 2, or 3). It seems as if the subdivision tones all functioned as a single unit for purposes of temporal reference, at least when they were unperturbed. This could be due to perceptual grouping at temporal separations below 300 ms or so (Hibi, 1983). The IOIs of subdivision tones in the 3s and 4s conditions ranged from 135 to 240 ms and thus were within the range in which integrated processing of successive events may occur. Alternatively, a single subdivision tone, probably the last one, may have served as a temporal reference, with the others having no additional effect. However, the PCRs to subdivision-level EOSs suggest that the subdivision tones were perceptually differentiated.

In all conditions in which an EOS occurred in a subdivision location, the PCR was stronger at the slow than at the fast tempo. As already mentioned, this is consistent with a stronger dependence of the taps on sequence timing at a slow tempo. The same argument, however, would seem to predict a reversal of the tempo effect in those conditions in which an unperturbed subdivision tone intervened between a subdivision-level EOS and the critical tap, because in those cases the PCR should depend more strongly on the unperturbed tone at the slow tempo than at the fast tempo. There were two such conditions: 3w1 (with w2 intervening) and 4w2 (with w3 intervening). The effect of tempo on the PCR

was indeed reduced in these conditions, but it was not reversed. Perhaps grouping of subdivision tones at these relatively fast rates prevented the most recent tone from acting as an independent reference for timing, or the tone was too close to the critical tap to serve as an effective reference. Both conditions, but especially the 4w2 condition, also showed a strong effect of EOS direction, with PCRs to negative EOSs being much smaller than those to positive EOSs. A negative EOS increased the temporal separation between the perturbed tone and the following unperturbed tone, thus perhaps making the latter more salient and more effective as a temporal reference. In the 4w2 condition in particular, the w2 tone may have been grouped with the w1 tone in the case of a negative EOS, and this may have released the w3 tone from the group and made it more salient.

Two differences among the subdivision-level EOS conditions are of particular interest. One is that the PCRs were larger in condition 4w2 than in condition 4w3 (Fig. 3d). This clearly shows that temporal proximity of the EOS to the tap was not the most important factor, and also that the unperturbed w3 tone was not effective in neutralizing the perturbation on w2. It suggests that the w2 tone, which bisected the IBI, was perceptually more important than the w3 tone (and presumably also more important than the w1 tone, which was never perturbed). In other words, this finding suggests a three-level metrical structure, or perhaps (at the fast tempo) a two-level structure with duple subdivision of the beat, in which the other subdivisions were not represented because they occurred too rapidly (cf. Repp, 2003). The other finding worth mentioning is that, in contrast to the ineffectiveness of an EOS located on w3 in quadruple subdivision (Fig. 3d), an EOS located on w2 in triple subdivision had a large effect, but only at the slow tempo (Fig. 3c). At the fast tempo, there was no PCR in either the 3w1 or 3w2 conditions. This interaction perhaps reflects a perceptual ungrouping of the two subdivision tones at the slower tempo, where they were separated by 240 ms.

In summary, the results of Experiment 1 suggest that the process of phase correction is sensitive to hierarchical metrical structure. The finding that the PCR was jointly determined by beat-level and subdivision-level timing shows that (at least) two levels of periodicity were involved in the control of sensorimotor coordination. In addition, evidence for stronger sensorimotor coupling at a slower tempo was found. Some specific effects seemed to reflect the relative strength of the grouping of successive subdivision tones. The results also demonstrate that phase correction in synchronization depends not (or not only) on tap-tone asynchronies but also on perceptual monitoring of intervening sequence events, as already noted by Large et al. (2002).

Experiment 2

The purpose of Experiment 2 was to make sure that the main findings of Experiment 1 were not in some way

peculiar to the task of omitting one tap, and that they are robust enough to show up when tapping is uninterrupted and the PCRs consequently are smaller. Only one beat tempo (the faster one of Experiment 1) was used in Experiment 2, and participants tapped on a different device than previously, which produced more auditory and tactile feedback.

Methods

Participants

Seven new paid volunteers (5 women, 2 men) and the author participated. Their ages and tapping experience were comparable to those of the participants in Experiment 1, but their musical experience was higher on average (three professional-level musicians, none without musical training). All participants were right-handed and tapped with their right hand.

Materials

The conditions and sequences were the same as in Experiment 1 (Fig. 2), but only the shorter IBI of 540 ms was used. There were no cue tones, so that all beat tones had the same pitch. Thus there were 11 (conditions) \times 2 (EOS magnitudes) + 4 (baseline) = 26 sequences, which were arranged into nine random orders.

Procedure

The experiment consisted of a single session lasting less than 1 h. Participants tapped on a Roland SPD-6 electronic percussion pad, which was held on the lap and provided some direct auditory feedback from the finger contact (a thud). Trials were self-paced: Participants pressed the space bar of the computer keyboard to start each sequence, which commenced 2 s later.

Results

The results for beat-level EOSs (Fig. 4a) replicated the fast-tempo results of Experiment 1, only the PCRs were smaller, as expected when tapping is continuous. The PCRs in all conditions were significantly different from zero. In contrast to Experiment 1, the difference between conditions was not significant, $F(3,21) = 2.6$, $P < 0.13$, $\epsilon = 0.50$. However, one participant showed a negative PCR to the positive EOS in condition 1s, which suggests an unusual compensatory strategy. With that participant omitted, the difference among conditions did reach significance, $F(3,18) = 4.5$, $P < 0.05$, $\epsilon = 0.57$.

The results for duple subdivision (Fig. 4b) again matched the Experiment 1 results at the faster tempo,

apart from the difference in absolute PCR magnitude. There were no significant effects of condition or EOS direction here.

The results for triple subdivision (Fig. 4c) deviated slightly from those of the fast tempo condition of Experiment 1 in that they showed a significant PCR in the 3w2 condition, whereas the PCR in the 3w12 condition was negligible. However, they confirmed the finding of a larger response to a beat-level EOS than to any subdivision-level EOS at the fast tempo. The difference between conditions was significant, $F(3,21) = 6.8$, $P < 0.02$, $\epsilon = 0.52$. When the 3s condition was omitted from the ANOVA, the difference between conditions did not reach significance.

The results for quadruple subdivision (Fig. 4d) confirmed the fast-tempo results of Experiment 1, except for a nonsignificant PCR in the 4w123 condition. Although only the PCRs in the 4s and 4w2 conditions were significantly greater than zero, the difference between conditions did not reach significance, $F(3,21) = 4.0$, $P < 0.07$, $\epsilon = 0.47$.

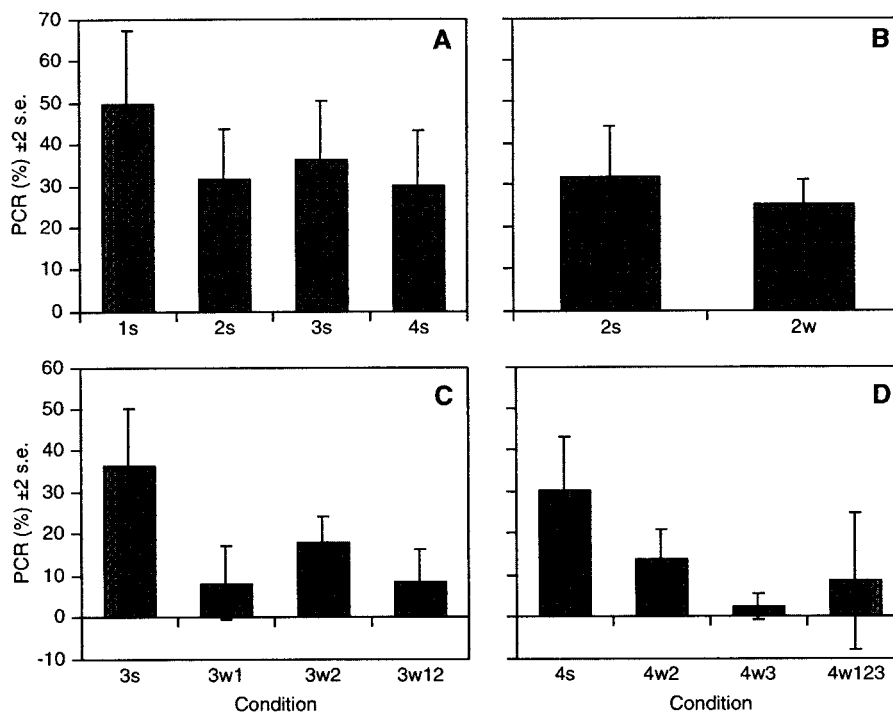
Discussion

By basically confirming the results of Experiment 1 for a fast tempo, the results of Experiment 2 show that the previous findings were not specific to the unusual task of omitting one tap. Although the mean PCRs were smaller than in Experiment 1, as expected, they were larger than in some previous studies using the EOS paradigm (Repp, 2002a, 2002d). This may have been a consequence of the larger variety of stimulus sequences, or perhaps the participants did not try as hard as previous participants to avoid reacting to the EOSs. For the purpose of the present research, the absolute size of the PCRs does not matter, as long as they are significantly greater than zero. The low statistical reliability of the differences between conditions suggests, however, that more data per condition might be desirable in the standard EOS paradigm. This was heeded in the subsequent experiments, which addressed several ways (other than varying tempo) in which the relative salience of the beat and subdivision levels in a two-level metrical hierarchy might be manipulated.

Experiment 3

Experiment 3 addressed the question of whether, or to what extent, the two effects of a subdivision tone (its ability to inhibit the PCR to a beat-level EOS when unperturbed, and its ability to elicit a PCR when perturbed) depend on the presence of subdivisions throughout a sequence. Would a single subdivision tone inserted into a sequence consisting solely of beats be just as effective? On one hand, the local stimulus configuration is exactly the same. On the other hand, only subdivisions that are continuously present (called

Fig. 4 Results of Experiment 2, with double standard errors. PCR phase correction response



global henceforth) firmly establish a two-level metrical hierarchy, so that a single (local) subdivision tone may be perceived as an unexpected intruder into a single-level metrical structure. Another way of formulating this hypothesis is that global subdivisions entrain an additional attentional oscillator with half the period of the beat-level oscillator (Large & Jones, 1999), whereas no such entrainment (or much weaker entrainment) occurs in the absence of global subdivisions. Therefore, it was predicted that a local subdivision would be less effective (and possibly completely ineffective) in blocking a PCR to a beat-level EOS and in eliciting a PCR on its own.

Experiment 3 differed from the preceding experiments in some other respects, which are described in more detail in the Methods section: (1) Beat tones and subdivision tones were physically identical rather than differentiated by intensity and pitch. (2) Several magnitudes of EOS were used in each condition, and a single PCR estimate was obtained as the slope of a linear function relating EOS and PCR magnitudes. Furthermore, the PCR was measured relative to the preceding tap, not relative to a baseline condition without an EOS. (That procedure had to be adopted in Experiment 1 because the preceding tap was missing, and it was maintained in Experiment 2 for the sake of comparison.) (3) The EOS could occur in different positions and thus was less predictable than in previous experiments. (4) Only duple subdivision was considered, at a fixed beat tempo similar to the one used in Experiment 2. (5) A new condition was added—a simultaneous onset shift of a beat and the following subdivision—to see whether the PCR to this combined EOS would be larger than the PCR to the separate EOSs.

Methods

Participants

Seven paid volunteers (3 men, 4 women), one of whom had participated in Experiment 2, and the author participated. Their ages and tapping experience were comparable to those of previous participants, but they were even more highly trained as musicians. (They included four professional-level musicians, two amateur drummers, one experienced amateur pianist, and one participant with merely 6 years of musical instruction.) Six participants were right-handed and tapped with the right hand. One of the two left-handers also found it more comfortable to tap with the right hand, whereas the other one tapped with the left hand.

Materials

The design of the sequences is shown schematically in Fig. 5. In the global subdivision condition, subdivisions were present from the third beat onward (the first two IBIs were always empty), except in the beat EOS (baseline) subcondition. In the local subdivision condition, only a single subdivision tone occurred, except in the beat EOS (baseline) subcondition, which was identical to that in the global subdivision condition. An EOS could occur on a beat without a following subdivision (beat EOS), on a beat followed by an unperturbed subdivision (beat EOS + sub), on a subdivision (sub EOS), or on both a beat and the following subdivision (beat + sub EOS), in which case both tones were shifted as a group.

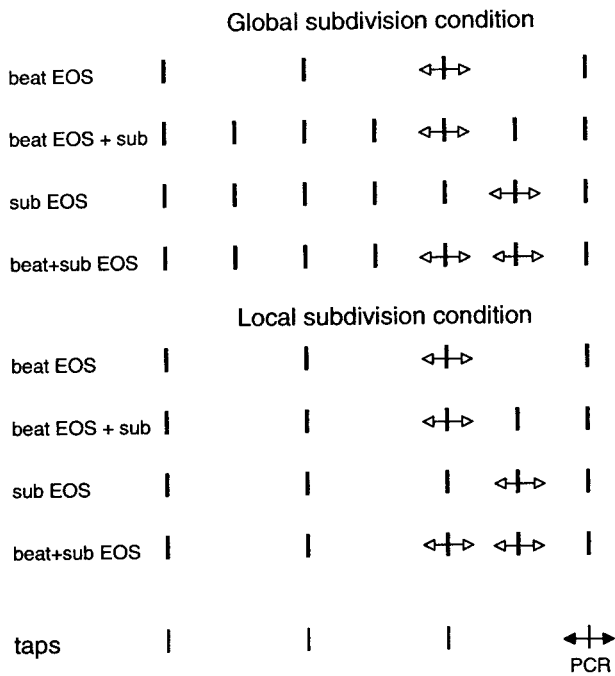


Fig. 5 Sequence design in Experiment 3. Only the critical segments of the sequences are shown. *EOS* event onset shift (symbolized by arrows with unfilled heads); *sub* subdivision; *PCR* phase correction response (symbolized by arrows with filled heads)

Sequences consisted of identical digital piano tones having the musical pitch of E_7 (2,637 Hz) and a nominal duration of 14 ms (with some decay following). Each sequence contained between 9 and 12 beat-level tones. The IBI was 560 ms, and the subdivision IOI was 280 ms. The EOS occurred on beat 6, 7, 8, or 9, or on the subdivision tone following that beat, and there were always three beats following the EOS (i.e., sequence length depended on EOS position). The EOS magnitudes were -28 , -14 , 0 , $+14$, and $+28$ ms. Thus there were $[4 \text{ (EOS conditions)} \times 5 \text{ (EOS magnitudes)} - 2] \times 4 \text{ (positions)} = 72$ different sequences in each of the two subdivision conditions (global, local). The “ -2 ” is explained by the fact that the beat EOS + sub, sub EOS, and beat + sub EOS conditions are identical when EOS = 0. The 72 sequences were grouped into four blocks of 18 randomly ordered sequences each, such that each sequence type occurred once in each block, and each EOS position occurred at least four times. The four blocks were replicated three times, with different random orders, so that there were 12 blocks altogether in each subdivision condition.

Equipment and procedure

The global and local subdivision conditions were run in separate sessions, typically 1 week apart, with half the participants doing the global condition first, and the other half the local. Equipment and procedure were the same as in Experiment 2, except that sequence

presentation and recording of taps were controlled by a program written in MAX/MSP 4.0.9 running on an iMac computer. (Footnote 3 applies no longer henceforth.)

Analysis

Relative times of occurrence of taps were computed and averaged across the 12 replications of each of the 18 sequence types, after aligning the data with respect to the sequence position of the EOS.⁵ The PCR for each EOS magnitude in each EOS condition was computed as the mean shift of the critical tap (occurring at time t_c) from its expected time of occurrence (i.e., as if there were no phase correction), defined as the time of occurrence of the preceding tap (t_{c-1}) plus the IBI. Thus, $PCR = t_c - (t_{c-1} + 560)$. In each EOS condition, the PCRs for the five EOS magnitudes were then plotted as a function of EOS magnitude, and a linear regression analysis was performed, which typically captured the data well. The slope of the regression line times 100, which expresses the PCR as a percentage of the EOS, was the overall measure of the PCR in each condition.

Results

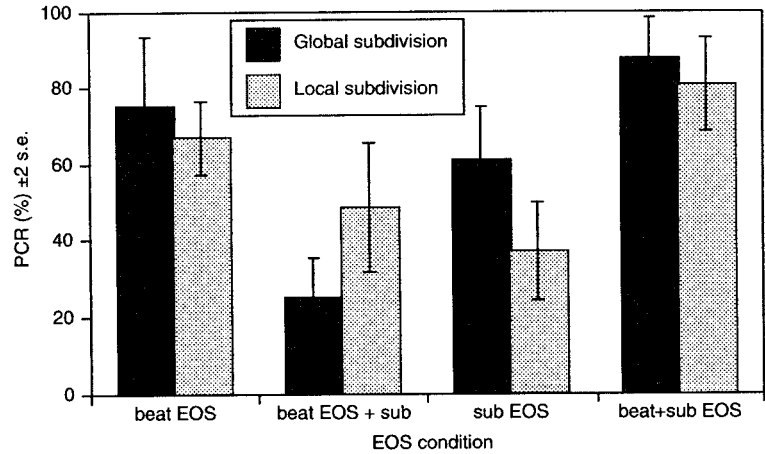
The results are shown in Fig. 6. Overall, the PCRs were surprisingly large (as percentages), which may be due to the smaller magnitudes of the EOSs compared to Experiment 2, and perhaps also to the musical expertise of the participants, which made them especially sensitive to temporal perturbations (even though they had been told not to react to any temporal irregularities). An overall 2×4 repeated-measures ANOVA revealed a significant main effect of EOS condition, $F(3,21) = 22.0$, $P < 0.001$, $\epsilon = 0.48$, as well as a significant interaction between subdivision condition (global vs. local) and EOS condition, $F(3,21) = 6.0$, $P < 0.005$, $\epsilon = 0.78$. Thus, global versus local subdivision indeed made a difference.

To consider the differences among conditions in more detail, separate 2×2 ANOVAs were conducted on pairs of EOS conditions. Consider first the beat EOS and beat + sub EOS conditions. Subdivision condition had no main effect on these EOS conditions, nor did it interact with EOS condition. Only the main effect of EOS condition reached significance, $F(1,7) = 6.6$, $P < 0.04$, because the PCRs were somewhat larger in the beat + sub EOS condition than in the beat EOS condition. This was as expected.

A comparison of the other two EOS conditions (beat EOS + sub and sub EOS) confirmed that these conditions were responsible for the overall interaction

⁵Relative times of occurrence are defined as the asynchronies of taps relative to an isochronous 560-ms time grid initiated by the first beat-level tone.

Fig. 6 Results of Experiment 3, with double standard errors. EOS event onset shift; PCR phase correction response



between subdivision condition and EOS condition. The 2×2 interaction was significant, $F(1,7) = 18.0$, $P < 0.005$, and its form was exactly as predicted: an unperturbed subdivision reduced the PCR to a beat-level EOS more in the global than in the local subdivision condition, and a subdivision EOS elicited a larger PCR in the global than in the local subdivision condition. It is noteworthy, however, that a local subdivision not only inhibited the PCR to a beat-level EOS but also elicited a significant PCR when perturbed.

Discussion

On the whole, the results of Experiment 3 support the hypothesis that global subdivision of IBIs creates a two-level metrical structure and thereby establishes or enhances the functional significance of the binary subdivision level. As predicted, an unperturbed subdivision tone was more effective in inhibiting the PCR to a beat EOS, and a perturbed subdivision tone was more effective in generating a PCR, when the subdivision tone occurred in the context of global subdivisions than when it occurred as a local intruder. However, even a local subdivision was quite effective in both respects, so it is by no means the case that an unexpected subdivision tone is irrelevant to synchronization.

How might such a local subdivision have its effect? One possibility is that participants engaged in mental subdivision of the IBIs and thereby created a two-level metrical structure internally in each trial without explicit physical support. Although the instructions did not prohibit such a strategy, it seems somewhat implausible because the IBIs were within the preferred beat range and thus did not invite spontaneous subdivision, as longer IBIs might. Also, local and global subdivision conditions were run in separate sessions, because mixing them might have encouraged mental subdivision in sequences that were not globally subdivided. Although half the participants experienced the global subdivision condition first, session order did not seem to have any effect. Still, it is possible that some participants engaged

in global mental subdivision in the local subdivision condition. The possible role of mental subdivision was investigated further in Experiment 5.

If participants did not subdivide mentally (and the author, at least, can testify that he did not), then the effectiveness of a local subdivision suggests that at least a binary subdivision level is always implicit when listening to a sequence of isochronous beats, as long as the IBIs are not too short for subdivision. For an EOS on a local subdivision tone to have its effect, there must be a temporal expectation about when the subdivision tone should occur (cf. Large & Jones, 1999); otherwise, the phase correction process would not receive any information about whether the tone was early or late. In the absence of any stimulus sequence that directly entrains the subdivision level, that level may then be thought of as an implicit harmonic of the beat period, as suggested by Desain (1992) in his connectionist model of rhythm perception. Thus, even an isochronous sequence may actually entrain a hierarchy of internal oscillators or timekeepers whose periods are related by simple ratios. Another way of framing the same thoughts is that participants must have been ready to reset the phase of their taps by “measuring” either a whole or half a beat period from the last tone they heard.

Experiment 3 was concerned with the extent to which metrical subdivision depends on the physical presence of subdivision tones. By contrast, Experiments 4, 5 and 6 explored ways in which the participants’ own cognitive or motor strategies might enhance the relative salience of the subdivision level. Experiments 4, 5 and 6 were conducted at about the same time, and different participants did them in different orders, usually 1 week apart.

Experiment 4

Experiment 4 employed a design similar to that of the local subdivision condition of Experiment 3, but the task was changed from in-phase to anti-phase tapping. The in-phase tapping data from Experiment 3 served for (within-participant) comparison. Anti-phase tapping

requires synchronization of taps with the perceived midpoints of the IBIs—that is, with the subdivision level. The taps thus effectively create the subdivision level or, if that level is already implicitly present, could at least be expected to enhance its relative salience in the mental representation of the metrical structure. If that were the case, then (1) an unperturbed subdivision tone following a beat EOS should become a more effective blocker of the PCR, and (2) the PCR to a subdivision EOS should be larger than in in-phase tapping. Note, however, that the first of these two predictions cannot be investigated easily because the anti-phase tap exhibiting the PCR coincides with the subdivision tone and hence cannot show the blocking effect of that tone. Therefore, the inhibiting effect of an intervening unperturbed beat on the PCR to a preceding subdivision EOS was examined instead. If the subdivision level is of relatively high salience in anti-phase tapping, that inhibiting effect should be relatively small. A test of the second prediction requires omission of the beat following the subdivision EOS.

Methods

Participants

The participants were the same as in Experiment 3.

Materials

The design of the sequences is illustrated schematically in Fig. 7. The conditions were locally identical with those in Experiment 3, but the functional roles of beats and subdivisions were interchanged. The beat EOS condition for anti-phase tapping corresponds to the sub EOS condition in in-phase tapping: In each case, the critical tap occurs about $IBI/2$ ms after a perturbed tone. The sub EOS no beat condition for anti-phase tapping corresponds to the beat EOS condition for in-phase tapping: In each case, the critical tap occurs about IBI ms after a perturbed tone. The sub EOS + beat condition in anti-phase tapping corresponds to the beat EOS + sub condition in in-phase tapping: In each case, a perturbed tone is followed by an unperturbed tone, which in turn is followed by the critical tap after about $IBI/2$ ms. Finally the sub + beat EOS condition in anti-phase tapping is like the beat + sub EOS condition in in-phase tapping. However, the beat EOS conditions in in-phase and anti-phase tapping can also be compared directly, as can the sub EOS conditions. In that case, the difference lies in how soon the critical tap occurs after the EOS.

In all other respects, the sequences and trial blocks were like those in Experiment 3.⁶

⁶One type of sequence was missing in this design, namely sub EOS no beat with $EOS = 0$. During preparation of the materials it was overlooked that this sequence is not identical with the $EOS = 0$ versions of sub EOS + beat and sub + beat EOS.

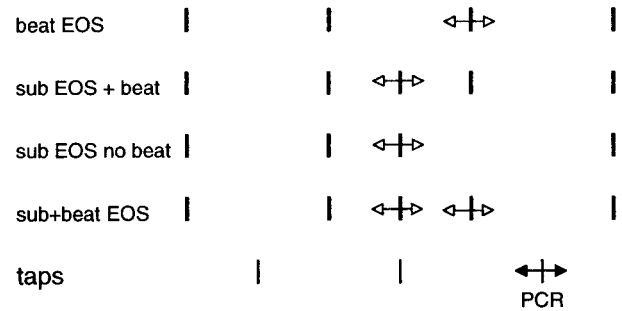


Fig. 7 Sequence design in Experiment 4. Only the critical segments of the sequences are shown. *EOS* event onset shift (symbolized by arrows with unfilled heads); *sub* subdivision; *PCR* phase correction response (symbolized by arrows with filled heads)

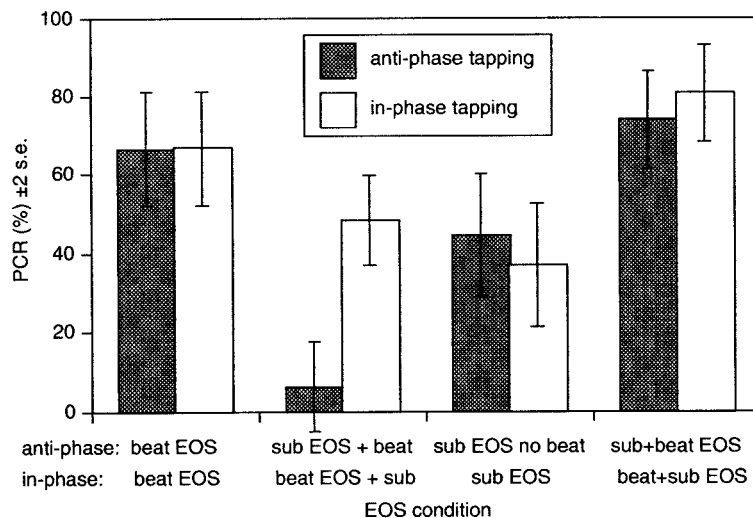
Equipment and procedure

These were the same as in Experiment 3, except for the instruction to tap in anti-phase, starting after the third sequence tone. Participants were alerted to the possible absence of one beat in the sequence. The experiment required a single session of less than 1 h.

Results

The results are shown in Fig. 8, together with the in-phase tapping (local subdivision) data from Experiment 3 for comparison. It is evident that there was little difference between the PCRs in anti-phase and in in-phase tapping for three of the four comparisons between corresponding conditions. Given the way in which the conditions are paired in the figure, this implies that it did not really matter how soon the critical tap occurred after the EOS. Moreover, these results imply that the relative salience of beats and subdivisions was similar in anti-phase and in-phase tapping: The PCR to a beat EOS was not smaller, and the PCR to a subdivision EOS was not larger, in anti-phase than in in-phase tapping. A large difference did occur, however, in the fourth comparison: An unperturbed beat following a subdivision EOS in anti-phase tapping was a much more effective blocker of the PCR than was an unperturbed subdivision following a beat EOS in in-phase tapping. In fact, the PCR in the sub EOS + beat condition was not significantly different from zero. An overall two-way repeated-measures ANOVA showed the differences between conditions, $F(3,21) = 32.4$, $P < 0.001$, $\epsilon = 0.68$, as well as the Experiment \times Condition interaction, $F(3,21) = 8.2$, $P < 0.002$, $\epsilon = 0.84$, to be significant. A separate comparison of the beat EOS + sub and sub EOS + beat conditions was also highly significant, $F(1,7) = 45.1$, $P < 0.001$. However, a comparison of the PCR reductions in the beat EOS + sub (Experiment 3) and sub EOS + beat (Experiment 4) conditions relative to the beat EOS and sub EOS conditions, respectively, fell short of significance, $F(1,7) = 4.3$, $P < 0.08$.

Fig. 8 Results of Experiment 4 together with the local subdivision results of Experiment 3, with double standard errors. EOS event onset shift; *sub* subdivision; PCR phase correction response



Discussion

The results of this experiment do not support the hypothesis that anti-phase tapping would increase the relative salience of the subdivision level. On the contrary, it seems that the beat level was as important, if not more important, in anti-phase tapping than in in-phase tapping. Whereas an unperturbed subdivision following a beat EOS merely reduced the PCR in in-phase tapping (Experiment 3), an unperturbed beat following a subdivision EOS blocked the PCR completely in anti-phase tapping. Moreover, a subdivision EOS did not elicit a larger PCR in anti-phase than in in-phase tapping. The results thus negate a special role for tap-tone asynchronies in anti-phase tapping: Phase correction relied more on the preceding beat as a temporal reference than on the subdivision tone that coincided with the preceding tap.

In hindsight, it is really not surprising that the beat is the primary temporal reference in anti-phase tapping. After all, the tapping is said to be in anti-phase for that very reason. The situation might be different if participants were instructed to consider their taps as the beats and the beat tones as the subdivisions. This strategy is hardly ever adopted spontaneously, but it might be worth investigating in a future study.

Experiment 5

Experiment 5 investigated another possible way of enhancing the relative salience of the subdivision level, namely to ask participants to imagine subdivisions of the beat. Mental subdivision is a task familiar to musicians who may be called upon to hear the same piece as being “in two” or “in four,” or who may engage in such strategies for the purpose of achieving greater rhythmic precision in solo performance, for example in syncopated passages. Using the local subdivision design of Experiment 3, Experiment 5 tested whether mental

subdivision enhances the effectiveness of a local subdivision tone in blocking the PCR to a beat EOS and in eliciting a PCR on its own when perturbed.

Methods

Participants

The participants were the same as in Experiments 3 and 4.

Materials

The sequences were like those employed in the local subdivision condition of Experiment 3 (but without the beat + sub EOS sequences). From those sequences, an additional set was created in which the first two IBIs were explicitly subdivided with tones identical to the beat tones. This resulted in 2 (initial subdivision or not) × 3 (EOS conditions) × 4 (EOS locations) × 5 (EOS magnitudes) = 120 sequences, which were presented twice in 10 blocks of 24.

Equipment and procedure

These were the same as in Experiment 3, except for the following change in instructions: When a sequence started slow (without subdivision), participants should start tapping on the third beat (the third tone) and should *not* imagine subdivisions. When a sequence started fast (initial subdivision), participants also should start tapping on the third beat (here the fifth tone) and should continue in their mind the binary subdivisions indicated by the beginning of the sequence. Exactly how the subdivisions should be imagined (e.g., as sounds, counts, or other actions) was not prescribed, but participants were urged not to make any overt movements of limbs or speech organs at the subdivision points.

Results

The results are shown in Fig. 9. The differences between EOS conditions replicate those obtained in Experiment 3 and are significant, $F(2,14) = 7.5$, $P < 0.02$, $\epsilon = 0.81$. Mental subdivision had little effect on the PCR to a beat EOS (baseline), where no effect was predicted. However, it also did not increase the effectiveness of a subdivision in reducing a beat-level PCR. By contrast, it did tend to increase the PCR to a subdivision EOS. The two-way interaction fell short of significance, $F(2,14) = 3.2$, $P < 0.08$, $\epsilon = 0.95$, but a separate comparison of the sub EOS conditions yielded a significant effect of mental subdivision, $F(1,7) = 11.0$, $P < 0.02$. Inspection of individual data suggested that five participants showed the predicted effect, whereas three (two professional musicians and the author) did not.

Discussion

This experiment revealed some effects of mental subdivision, but not for all participants. The effects were asymmetric in that mental subdivision increased the PCR to a subdivision EOS but did not increase the subdivision's effectiveness in blocking the PCR to a preceding beat EOS.

Participants were interviewed informally about their subdivision strategies, which not surprisingly involved either counting (i.e., inner speech) or imagining sounds. Their strategy seemed to be unrelated to whether or not they showed an effect of mental subdivision. Given that mental subdivision is a purely subjective activity, it is noteworthy that it had any measurable effect at all.

Experiment 6

The final experiment in this series engaged the participants' other hand to mark subdivisions (or not). Using the same sequences as in Experiment 5, participants were

instructed to tap either with both hands simultaneously (both hands tapping in phase) or in alternation (one hand tapping in phase with beats, and the other hand tapping in anti-phase with beats and in phase with subdivisions). The question was whether marking the subdivisions with the other hand would increase the effectiveness of local subdivision tones in blocking the beat hand's PCR to a beat EOS and in eliciting a PCR to a subdivision EOS in the beat hand. The PCRs of the subdivision hand were also of interest (as they were in the anti-phase tapping task of Experiment 4).

Methods

Participants

The participants were the same as in Experiments 3, 4 and 5.

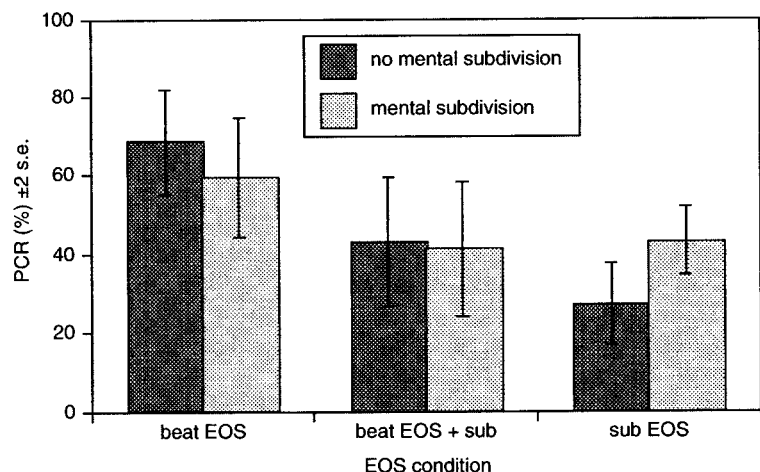
Materials

The sequences were the same as in Experiment 5.

Equipment and procedure

The equipment was the same as previously. Instead of tapping on the upper middle segment of the electronic percussion pad (which had six segments), participants tapped on the upper left and upper right segments with the index fingers of the left and right hands, respectively. Whenever a sequence started slow (no initial subdivision), participants were to tap in phase with both hands simultaneously, starting with the third beat (the third tone). Whenever a sequence started fast (with two subdivided IBIs), participants were to tap with the two hands in alternation, starting on the third beat (the fifth tone), such that one hand tapped in phase with the beats and the other hand marked the subdivisions. Six participants (including the left-hander who had tapped with

Fig. 9 Results of Experiment 5, with double standard errors. EOS event onset shift; *sub* subdivision; PCR phase correction response



the right hand in previous experiments) marked the beats with the right hand, whereas two (the left-hander who had tapped with the left hand in previous experiments, and one right-hander who misunderstood the instructions) used the left hand for the beats. Participants were encouraged to tap with equal force with their two hands.⁷

Results

The PCR results for the beat hand are shown in Fig. 10a. It is evident that active subdivision had no effect at all on the PCRs. The differences among conditions, $F(2,14) = 12.1$, $P < 0.007$, $\epsilon = 0.58$, are similar to those obtained in previous experiments.

Figure 10b shows the PCRs of the other hand. When that hand tapped on the beat (in phase with the beat hand), the PCRs were similar to those of the beat hand, as expected. When it tapped subdivisions, two differences emerged. In the beat EOS + sub condition, the subdivision tap coincided with the local subdivision tone and therefore could not benefit from that tone as a temporal reference. Consequently, the PCR was as large as that to a beat EOS without a following subdivision. Because, for the same reason, the subdivision tap coinciding with a subdivision EOS (in the sub EOS condition) could not exhibit a PCR yet, the right-most bar in Fig. 10b shows instead the PCR exhibited by the subsequent tap, which was separated from the local subdivision by an unperturbed beat. That beat largely blocked the PCR to the subdivision EOS, as it had done in the anti-phase tapping task of Experiment 4 (Fig. 8). However, although the main effect of condition reached significance, $F(2,14) = 8.3$, $P < 0.02$, $\epsilon = 0.59$, the Condition \times Subdivision interaction did not, $F(2,14) = 4.3$, $P < 0.08$, $\epsilon = 0.56$.

Discussion

Active subdivision of IBIs by a motor response had no effect at all on the PCRs. Apparently, the actions of the other hand did not enhance the subdivision level and thus did not make the local subdivision tone any more salient when it occurred.

General discussion

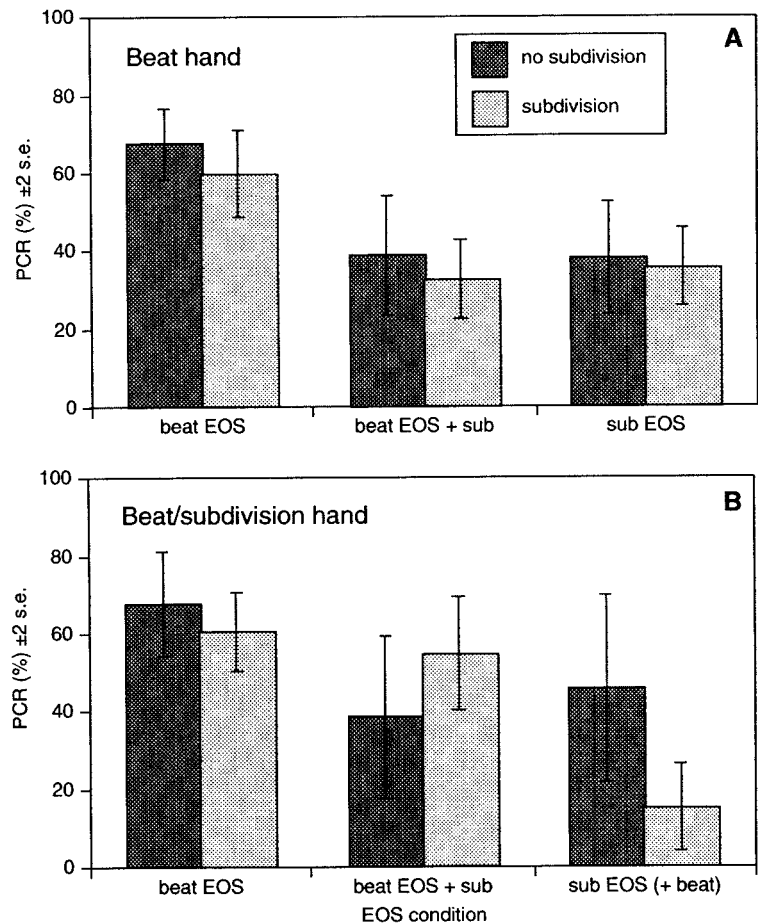
The primary question addressed by this study was whether hierarchical metrical structure plays a role in sensorimotor synchronization in the sense that it provides multiple temporal references for phase error correction or phase resetting. In each experiment, a (minimally) two-level metrical structure was created from an isochronous sequence by requiring participants to tap only with every n th tone. This action was assumed to confer the status of main beat (tactus) on the tones that coincided with the taps, whose frequency in any case was in the appropriate range (Parncutt, 1994; van Noorden & Moelants, 1999). The intervening tone(s) were assumed to function as subdivisions. The dependent variable was the unintended PCR to an EOS occurring either on the beat level or on the subdivision level (or sometimes on both).

Two extreme hypotheses were considered in the Introduction: According to one, derived from an asynchrony-based theory of phase error correction, only perturbations of beats should elicit a PCR. According to the other hypothesis, derived from a simple variant of a phase resetting theory, only perturbations of the most recent sequence event (usually a subdivision) should have an effect. Neither hypothesis was supported: In each experiment, perturbations on both the beat level and the subdivision level elicited a PCR. These results are consistent with a hypothesis according to which all levels in a metrical hierarchy are monitored perceptually and serve as temporal references in phase correction or resetting. Such a hypothesis is part and parcel of a dynamic pattern formation approach to metrical structure, particularly that of Large (2000, 2001; Large & Kolen, 1994; Large & Palmer, 2002). The results are in agreement with the empirical findings of Large et al. (2002), who used different types of perturbation in more complex rhythmic sequences, and with the preliminary findings of Repp (2002a).

According to current information-processing models of phase correction in sensorimotor synchronization, the asynchronies between (nearly) coincident tones and taps provide the perceptual information on which corrections of action timing are based. The present results show that this view is too narrow. One way of interpreting the data is that asynchronies are used as the basis of phase correction when they are available, but that in addition other sequence events are monitored perceptually and used as external temporal references. A more parsimonious interpretation, however, is that beats and subdivisions are both monitored perceptually and serve as external references, and that asynchronies do not play any direct role. This interpretation receives additional support from the anti-phase tapping results of Experiments 4 and 6, which suggest that subdivision-level asynchronies play hardly any role at all. Asynchronies thus may not be as important perceptually as has been thought, at least when they are small in size. Large

⁷Evidently, this last instruction was difficult to follow. Three participants tapped so lightly with their left (subdivision) hand that the taps sometimes were not registered. This happened particularly when the subdivision hand tapped in phase with the beat hand. As this was the least interesting part of the data (the two hands were expected to show similar PCRs when tapping in phase with each other), no steps were taken to correct this problem. For each participant, there were still sufficient trials with complete data to compute an (albeit less reliable) estimate of the PCR in the subdivision hand.

Fig. 10 Results of Experiment 6, with double standard errors. *EOS* event onset shift; *sub* subdivision; *PCR* phase correction response



asynchronies that are consciously detected may lead to deliberate period correction rather than automatic phase correction (cf. Repp & Keller, 2004; Schulze, Cordes, & Vorberg, 2005). The fact that phase correction is imperfect and takes several taps to complete can be attributed to a tendency to maintain the tapping period (Repp, 2002c), which is equivalent to saying that the preceding tap serves as an additional temporal reference (Hary & Moore, 1985, 1987).

The present study also examined different ways in which the relative salience of the beat and subdivision levels as temporal references might be changed. Experiment 1 demonstrated that the relative perceptual weights of the beat and subdivision levels in a two-level metrical structure depend strongly on tempo. At a fast tempo, the beat level increased in relative importance because it was within the region of optimal period durations for a beat (Parncutt, 1994; van Noorden & Moelants, 1999), whereas the subdivision level was outside that region. At the slower tempo, the subdivisions became a potential beat and therefore started to compete with the beat level for attention. Or, in other words, the internal oscillator entrained to the subdivisions gained in amplitude relative to the oscillator entrained to the beat. In the perturbation paradigm used here, an increase in the relative salience of the subdivision level was reflected in two

ways: The inhibiting effect of an unperturbed subdivision on the PCR to a preceding beat EOS increased, and a subdivision EOS elicited a larger PCR.

A possibly related phenomenon has been considered in mathematical modeling of 1:1 synchronization performance: second-order phase correction (Pressing, 1998; Pressing & Jolley-Rogers, 1997; Semjen et al., 2000; Vorberg & Schulze, 2002). This means that not only the last but also the next-to-last asynchrony is considered to provide information for phase correction. Second-order phase correction tends to be negligible at moderate to slow tempi, but it emerges when the tempo gets fast and/or when the participant is an expert musician (Pressing, 1998). From the present perspective, this could be interpreted as being due to the spontaneous emergence of a two-level metrical structure at a fast tempo. In a 1:2 tapping task, the beat is more firmly established than in 1:1 tapping because the taps reinforce it (or define it), and this is reflected in a relatively larger contribution of beat-level (second-order) phase correction. However, the 1:3 and 1:4 tapping tasks of Experiment 1 suggest that it is indeed the beat level and not just the penultimate event that serves as a temporal reference. Phase correction appears to be governed by the hierarchical metrical organization imposed on the event sequence, not by the linear temporal succession of events.

Experiments 3, 4, 5 and 6 pursued various ways, other than changing the sequence tempo, in which the balance between the beat and subdivision levels might be changed. None of these ways was as effective as the tempo manipulation in Experiment 1. Experiment 3 showed that the relative importance of the subdivision level as a temporal reference is reduced when a single local subdivision occurs in a sequence of beats, compared to global subdivision. A reduction was observed in both effects of interest (the blocking of a beat-level PCR by an unperturbed subdivision, and the PCR to a perturbed subdivision). Still, even a single local subdivision tone was quite effective in both respects. Experiments 4, 5 and 6 replicated this finding, which suggests that the subdivision level is present in a latent form, even if there are no globally subdivided sequences in the entire experimental session.

One way in which such a latent subdivision level might be generated and maintained is by means of mental subdivision—the endogenous initiation and/or maintenance of an internal periodicity faster than the beat. Experiment 5 investigated whether intentional mental subdivision affects the salience of a local subdivision as a temporal reference. A consistent influence was found for only one of the two indicators, the PCR to a subdivision EOS. Local subdivisions remained quite effective as temporal references even when participants deliberately refrained from mental subdivision (assuming that they were able to follow these instructions). This suggests that the latent subdivision level does *not* reflect an endogenous mental process of subdivision but rather is an automatic consequence of entrainment to a beat (cf. Desain, 1992).

Experiments 4 and 6 examined whether tapping at the subdivision level would increase the relative salience of that level within the metrical structure. The results were essentially negative, regardless of whether participants tapped only subdivisions (anti-phase tapping, Experiment 4) or both beats and subdivisions (alternating hands, Experiment 6). These findings provide further evidence against the hypothesis that tone-tap asynchronies are the crucial perceptual information for synchronization and phase correction. Particularly in anti-phase tapping, asynchronies occurred *only* at the subdivision level, yet the beat level was as salient, if not more salient, than in in-phase tapping. Of course, this could have occurred only if participants thought of the beats as beats and of the taps as subdivisions, as they evidently did. To think of the taps as beats and of the tones as subdivisions, while a theoretical possibility, is hardly ever done spontaneously. Such a cognitive reversal was even less likely in Experiment 6, where the beat hand (the dominant hand in all but two participants) and the sequence tones reinforced each other.

From these findings it can be concluded that the relative salience of the beat and subdivision levels depends primarily on physical properties of the tone sequence (such as tempo and presence of continuous subdivisions) and secondarily on cognitive strategies (such as mental subdivision, though a deliberate reinterpretation of beats as subdivisions and vice versa

might have a more dramatic effect—this remains to be explored), but not on the motor activity and the form of sensorimotor coordination (in-phase, anti-phase, or alternating-hand tapping).

One unexpected but rather consistent finding was obtained in Experiments 3, 5, and 6, but was not mentioned earlier so as not to detract from the main issues: The mere occurrence of a local subdivision (i.e., without an EOS) caused a negative PCR, and that shift (measured as the zero intercept of the linear regression of PCR magnitude on EOS magnitude) was most pronounced on the *second* tap following the subdivision. This is in contrast to the PCR to an EOS, which is nearly always largest on the first tap following an EOS. The results seem to suggest that not only the local subdivision tone but also the following beat was perceived as occurring somewhat earlier than expected. However, this explanation is contradicted by the results of Experiment 4 (anti-phase tapping) because they did not show any negative shift of the taps after the beat that followed a local subdivision. Also, Wohlschläger and Koch (2000) have reported evidence that the commonly found negative mean asynchrony (or anticipation tendency) in sensorimotor synchronization is reduced when the IBI is subdivided by extra tones, which implies a *positive* shift of taps. The observed negative shift therefore probably has a different cause. It may have to do with perceptual grouping of the three closely spaced tones in the sequence (beat-subdivision-beat). In studies of rhythm and music production it has been found that such groups tend to be produced with a lengthened second interval (Drake & Palmer, 1993; Penel & Drake, 1998), and conversely the second interval needs to be lengthened if the pattern is to be heard as regularly timed (Penel & Drake, 2004). This may be the reason why the (precisely timed) beat following a local subdivision may have seemed to occur early.

In conclusion, the present results provide evidence that perceptual monitoring of an isochronous sequence can take place on at least two metrical levels simultaneously, and that sensorimotor synchronization relies on temporal information from this monitoring process, not (or not only) on tap-tone asynchronies.

Acknowledgments This research was supported by NIH grant MH-51230. Experiments 3, 4, 5 and 6 and preparation of the manuscript were also partially supported by NIH grants DC-03663 (Elliot Saltzman, P.I.) and HD-01994 (Carol Fowler, P.I.). Thanks are due to these colleagues for their generous support, to Yoko Hoshi, Helen Sayward, and Susan Holleran for help with data analysis, and to Amandine Penel, Susan Holleran, and Peter Keller for helpful comments on earlier versions of the manuscript. Experiment 1 was reported previously in Repp (2002b).

References

- Aschersleben, G. (2002). Temporal control of movements in sensorimotor synchronization. *Brain and Cognition*, 48, 66–79.
- 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.
- Aschersleben, G., Stenneken, P., Cole, J., & Prinz, W. (2002). Timing mechanisms in sensorimotor synchronization: Inter-sensory integration of action effects. In W. Prinz & B. Hommel (Eds.), *Attention and Performance XIX: Common mechanisms in perception and action* (pp. 227–244). Oxford, U.K.: Oxford University Press.
- Bolton, T. L. (1894). Rhythm. *American Journal of Psychology*, 6, 145–238.
- Byblow, W. D., Chua, R., & Goodman, D. (1995). Asymmetries in coupling dynamics of perception and action. *Journal of Motor Behavior*, 27, 123–137.
- Chen, Y., Ding, M., & Kelso, J. A. S. (1997). Long memory processes ($1/f^\alpha$ type) in human coordination. *Physical Review Letters*, 79, 4501–4504.
- Chen, Y., Ding, M., & Kelso, J. A. S. (2001). Origins of timing errors in human sensorimotor coordination. *Journal of Motor Behavior*, 33, 3–8.
- Chen, Y., Repp, B. H., & Patel, A. D. (2002). Spectral decomposition of variability in synchronization and continuation tapping: Comparisons between auditory and visual pacing and feedback conditions. *Human Movement Science*, 21, 515–532.
- 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.
- Desain, P. (1992). A (de)composable theory of rhythm perception. *Music Perception*, 9, 439–454.
- Drake, C., & Palmer, C. (1993). Accent structures in music performance. *Music Perception*, 10, 343–378.
- Eck, D. (2002). Finding downbeats with a relaxation oscillator. *Psychological Research*, 66, 18–25.
- Engström, D. A., Kelso, J. A. S., & Holroyd, T. (1996). Reaction-anticipation transitions in human perception-action patterns. *Human Movement Science*, 15, 809–832.
- Fraisse, P., Oléron, G., & Paillard, J. (1958). Sur les repères sensoriels qui permettent de contrôler les mouvements d'accompagnement de stimuli périodiques. [On the sensory data that enable control of movements accompanying periodic stimuli.] *L'Année Psychologique*, 58, 322–338.
- Franěk, M., Radil, T., & Indra, M. (1990). Subjective timing of rhythmical patterns during synchronization and reproduction of acoustic sequences. *Studia Psychologica*, 32, 203–209.
- Franěk, M., Mates, J., Radil, T., Beck, K., & Pöppel, E. (1991). Sensorimotor synchronization: Motor responses to regular auditory patterns. *Perception & Psychophysics*, 49, 509–516.
- Friberg, A., & Sundberg, J. (1995). Time discrimination in a monotonic, isochronous sequence. *Journal of the Acoustical Society of America*, 98, 2524–2531.
- 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.
- Keller, P. E., & Repp, B. H. (2004). When two limbs are weaker than one: Sensorimotor syncopation with alternating hands. *Quarterly Journal of Experimental Psychology*, 57A, 1085–1101.
- Keller, P. E., & Repp, B. H. (2005). Staying offbeat: Sensorimotor syncopation with structured and unstructured auditory sequences. *Psychological Research*, 69, 292–309.
- Kelso, J. A. S., DelColle, J. D., & Schöner, G. (1990). Action-perception as a pattern formation process. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 139–169). Hillsdale, NJ: Erlbaum.
- Large, E. W. (2000). On synchronizing movements to music. *Human Movement Science*, 19, 527–566.
- Large, E. W. (2001). Periodicity, pattern formation, and metric structure. *Journal of New Music Research*, 30, 173–185.
- Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How we track time-varying events. *Psychological Review*, 106, 119–159.
- Large, E. W., & Kolen, J. F. (1994). Resonance and the perception of musical meter. *Connection Science*, 6, 177–208.
- Large, E. W., & Palmer, C. (2002). Perceiving temporal regularity in music. *Cognitive Science*, 26, 1–37.
- Large, E. W., Fink, P., & Kelso, J. A. S. (2002). Tracking simple and complex sequences. *Psychological Research*, 66, 3–17.
- 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.
- Mates, J., Radil, T., Müller, U., & Pöppel, E. (1994). Temporal integration in sensorimotor synchronization. *Journal of Cognitive Neuroscience*, 6, 332–340.
- McAuley, J. D., & Jones, M. R. (2003). Modeling effects of rhythmic context on perceived duration: A comparison of interval and entrainment approaches to short-interval timing. *Journal of Experimental Psychology: Human Perception and Performance*, 29, 1102–1125.
- Nagasaki, H. (1987a). Correlations of stress and timing in periodic tapping. *Human Movement Science*, 6, 161–180.
- Nagasaki, H. (1987b). Frequency dependence of rhythm in periodic tapping. *Human Movement Science*, 6, 247–256.
- van Noorden, L., & Moelants, D. (1999). Resonance in the perception of musical pulse. *Journal of New Music Research*, 28, 43–66.
- Parncutt, R. (1994). A perceptual model of pulse salience and metrical accent in musical rhythms. *Music Perception*, 11, 409–464.
- Penel, A., & Drake, C. (1998). Sources of timing variations in music performance: A psychological segmentation model. *Psychological Research*, 61, 12–32.
- Penel, A., & Drake, C. (2004). Timing variations in music performance: Musical communication, perceptual compensation, and/or motor control? *Perception & Psychophysics*, 66, 545–562.
- Peper, C. E., & Beek, P. J. (1998). Distinguishing between the effects of frequency and amplitude on interlimb coupling in tapping a 2:3 polyrhythm. *Experimental Brain Research*, 118, 78–92.
- Peper, C. E., Beek, P. J., & van Wieringen, P. C. W. (1995). Coupling strength in tapping a 2:3 polyrhythm. *Human Movement Science*, 14, 217–245.
- 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.
- Repp, B. H. (1997). Acoustics, perception, and production of legato articulation on a computer-controlled grand piano. *Journal of the Acoustical Society of America*, 102, 1878–1890.
- Repp, B. H. (1999a). Detecting deviations from metronomic timing in music: Effects of perceptual structure on the mental time-keeper. *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.
- Repp, B. H. (2000). Compensation for subliminal timing perturbations in perceptual-motor synchronization. *Psychological Research*, 63, 106–128.
- Repp, B. H. (2001a). Phase correction, phase resetting, and phase shifts after subliminal timing perturbations in sensorimotor

- synchronization. *Journal of Experimental Psychology: Human Perception and Performance*, 27, 600–621.
- Repp, B. H. (2001b). Processes underlying adaptation to tempo changes in sensorimotor synchronization. *Human Movement Science*, 20, 277–312.
- Repp, B. H. (2002a). Automaticity and voluntary control of phase correction following event onset shifts in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance*, 28, 410–430.
- Repp, B. H. (2002b). Effects of metrical structure on phase resetting in sensorimotor synchronization. In C. Stevens, D. Burnham, G. McPherson, E. Schubert, & J. Renwick (Eds.), *Proceedings of the Seventh International Conference on Music Perception and Cognition* (pp. 572–574). Sydney: Causal Productions (CD-ROM).
- Repp, B. H. (2002c). Phase correction following a perturbation in sensorimotor synchronization depends on sensory information. *Journal of Motor Behavior*, 34, 291–298.
- Repp, B. H. (2002d). Phase correction in sensorimotor synchronization: Nonlinearities in voluntary and involuntary responses to perturbations. *Human Movement Science*, 21, 1–37.
- Repp, B. H. (2003). Rate limits in sensorimotor synchronization with auditory and visual sequences: The synchronization threshold and the benefits and costs of interval subdivision. *Journal of Motor Behavior*, 35, 355–370.
- Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review*, 12, 969–992.
- Repp, B. H., & Keller, P. E. (2004). Adaptation to tempo changes in sensorimotor synchronization: Effects of intention, attention, and awareness. *Quarterly Journal of Experimental Psychology*, 57A, 10.
- Schulze, H.-H. (1992). The error correction model for the tracking of a random metronome: Statistical properties and an empirical test. In F. Macar, V. Pouthas, & W. J. Friedman (Eds.), *Time, action, and cognition* (pp. 275–286). Dordrecht: Kluwer.
- Schulze, H.-H., Cordes, A., & Vorberg, D. (2005). Keeping synchrony while tempo changes: Accelerando and ritardando. *Music Perception*, 22, 461–477.
- Semjen, A., Schulze, H.-H., & Vorberg, D. (1992). Temporal control in the coordination between repetitive tapping and periodic external stimuli. In C. Auxiette, C. Drake, & C. Gérard (Eds.), *Proceedings of the Fourth Rhythm Workshop: Rhythm Perception and Production* (pp. 73–78). Bourges, France: Imprimerie Municipale.
- Semjen, A., Schulze, H.-H., & Vorberg, D. (2000). Timing precision in continuation and synchronization tapping. *Psychological Research*, 63, 137–147.
- Thaut, M. H., Miller, R. A., & Schauer, L. M. (1998). 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. (1998). Rhythmic finger tapping to cosine-wave modulated metronome sequences: Evidence of subliminal entrainment. *Human Movement Science*, 17, 839–863.
- Todd, N. P. McA., Lee, C. S., & O'Boyle, D. J. (2002). A sensorimotor theory of temporal tracking and beat induction. *Psychological Research*, 66, 26–39.
- Vorberg, D., & Hambuch, R. (1978). On the temporal control of rhythmic performance. In J. Requin (Ed.), *Attention and Performance VII* (pp. 535–556). Hillsdale: Erlbaum.
- Vorberg, D., & Hambuch, R. (1984). Timing of two-handed rhythmic performance. In J. Gibbon & L. Allan (Eds.), *Timing and time perception* (pp. 390–406). New York: New York Academy of Sciences (*Annals*, Vol. 423).
- Vorberg, D., & Schulze, H.-H. (2002). A two-level timing model for synchronization. *Journal of Mathematical Psychology*, 46, 56–87.
- 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.
- Vos, P. G., & Helsen, E. L. (1992). Tracking simple rhythms: In-phase versus anti-phase performance. In F. Macar, V. Pouthas, & W. J. Friedman (Eds.), *Time, action, and cognition: Towards bridging the gap* (pp. 287–299). Dordrecht: Kluwer.
- Wimmers, R. H., Beek, P. J., & van Wieringen, P. C. W. (1992). Phase transitions in rhythmic tracking movements: A case of unilateral coupling. *Human Movement Science*, 11, 217–226.
- Wohlschläger, A., & Koch, R. (2000). Synchronization error: an error in time perception. In P. Desain & L. Windsor (Eds.), *Rhythm perception and production* (pp. 115–128). Lisse, The Netherlands: Swets & Zeitlinger.