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RESEARCH ARTICLE

Temporal evolution of the phase correction response in synchronization of taps with perturbed two-interval rhythms

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Abstract Human sensorimotor synchronization is flexible but subject to temporal constraints. Previous research has shown that musicians tend to lose synchrony with target tones in an isochronous sequence when the sequence rate exceeds 8–10 Hz, presumably because phase correction ceases to function. The present study investigated directly the time required for an immediate phase correction response (PCR). Musicians tapped in synchrony with cyclic two-interval (short-long) rhythms, using the two hands in alternation. Perturbations were applied to the long interval, and the compensatory shift of the next tap (the PCR) was measured following the short interval, whose duration was varied from 100 to 300 ms. The PCR was found to increase gradually within this range, being nearly absent at 100 ms. Similar results were obtained when participants tapped only with the second tone in each rhythmic group, which confirms that the PCR is based on the preceding tone rather than on the preceding tap-tone asynchrony, and also when the second tone was omitted in the pacing sequence, which indicates that the PCR occurs automatically even when there is no synchronization target for the critical tap. These results extend earlier findings regarding rate limits of synchronization and also provide further support for an event-based phase resetting account of the PCR.

Keywords Synchronization · Tapping · Phase correction · Rhythm production · Action timing

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Although recent research has demonstrated sensorimotor synchronization abilities in birds (Patel et al. 2009; Schachner et al. 2009) and perhaps even non-human primates (Large et al. 2008), humans are unique in the flexibility of their synchronization skills, which find their primary application and highest development in musical activities (Keller 2008; Repp 2006a). Yet this flexibility has limits: Synchronization with external events becomes difficult when the event rate is either very high or very low, with the optimal range being roughly between 5 and .5 Hz, corresponding to event inter-onset intervals (IOIs) of 200–2,000 ms (Fraisse 1982; Repp 2006b).

The present study is concerned specifically with the high-rate (short-duration) temporal limits that impinge on the ability to synchronize. In early research on this topic, Bartlett and Bartlett (1959) observed that participants instructed to make a single tap in synchrony with any sound in a rapid isochronous series performed at chance level (i.e., showed a flat distribution of relative phases between taps and sounds) when the event rate was as high as 8 Hz. More recently, Repp (2003b) investigated this rate limit (which he dubbed "synchronization threshold") in more detail by asking participants, most of whom had some music training, to tap with every fourth tone of an isochronous sequence whose IOI duration was varied from 80 to 170 ms using the method of constant stimuli.[1] On average, synchronization broke down at a rate near 8 Hz (IOI = 125 ms), with phase wrapping occurring in more than 50% of trials at faster rates.

Subsequently, Repp (2005a) devised a simple adaptive staircase procedure to zero in on this synchronization

[1] Tapping with every tone would have exceeded the maximal unimanual tapping rate, which is about 6 Hz (Peters 1980; Truman and Hammond 1990).

threshold. He used isochronous as well as simple non-isochronous rhythms consisting of a cyclically repeated group of two or three tones, where the between-group interval (IOI_b) was twice as long as the within-group interval (IOI_w). The musically trained participants' task was to tap with one of the tones in each cycle or in the silent center of IOI_b. For a trial to be successful, all taps had to be within $IOI_w/2$ of the target points. The lowest mean thresholds (in terms of IOI duration) were obtained for tapping with the second tone of a group of two tones and with the first or third tone of a group of three tones (i.e., with tones carrying grouping accents; see Povel and Okkerman 1981), and they were again in the vicinity of a basic pulse rate of 8 Hz (i.e., IOI_w was near 125 ms). In a later study, Repp (2007) had his participants tap with every *n*th tone of an isochronous sequence, where *n* ranged from 2 to 9. For musically trained participants, he again found synchronization thresholds in the vicinity of IOI = 125 ms for $n = 2$, 3, 4, or 8. Other values of *n* resulted in higher thresholds, and a group of non-musicians showed much higher thresholds across the board.

Loss of synchronization and the resulting phase wrapping suggest a failure of phase correction, also called sensorimotor coupling or entrainment, the process that undergirds synchronization. It thus appears from the foregoing results that musicians' phase correction breaks down when IOIs get shorter than 125 ms, on average. In a review article, Repp (2006b) discussed several possible reasons for this breakdown. The temporal limit could be attentional, perceptual, or sensorimotor in nature. Specifically, it could reflect the rate limit of a neural oscillator that synchronizes modulations of attentional energy with external events (Large and Jones 1999); or it could be due to a temporal integration window that binds events together perceptually if they occur in very close succession (Yabe et al. 1998), so that they become difficult to distinguish as individual events; or, finally, it could reflect the time needed to make a phase adjustment in response to preceding information. The present study addresses this last hypothesis.

It is often assumed that asynchronies constitute the perceptual information on which phase correction is based (e.g., Mates 1994; Vorberg and Wing 1996), and from that perspective, it would be the perception and processing of asynchronies that requires some minimal time. However, various empirical results (reviewed in Repp 2005b) favor an alternative though formally equivalent conception originally suggested by Hary and Moore (1985, 1987), according to which phase correction constitutes phase resetting of each tap with reference to the most recent tone(s), while a simultaneous tendency to maintain the tapping rhythm inhibits the phase resetting and prevents it from being instantaneous. For example, Repp (2001) showed that phase correction in response to a timing perturbation (a phase shift) in an isochronous pacing sequence actually *improves* when the tap coinciding with the phase-shifted tone is omitted, so that there is no physical asynchrony on which phase correction could be based. The improvement was attributed to a reduction in the maintenance tendency, consequent upon disruption of the tapping rhythm by omission of one or more taps. From the perspective of this *phase resetting hypothesis*, then, the synchronization threshold is likely to reflect the time required for phase resetting based on the preceding tone or, in other words, the time required for changing the temporal goal of a planned and perhaps already initiated finger movement.

This last interpretation suggests an interesting parallel with studies of movements that are directed toward spatial goals, such as pointing or grasping. This research has shown that an unexpected perturbation of the target location leads to automatic adjustments of the movement trajectory, with participants often being unaware of the perturbation (e.g., Brenner and Smeets 1997, 2009; Gomi 2008; Hansen and Elliott 2009; Paulignan et al. 1991; Soechting and Lacquaniti 1983). The latency of the adjustment varies with experimental conditions but is typically between 100 and 200 ms. In other words, if the perturbation occurred only 100–200 ms before the target would have been reached, there would be insufficient time to adjust, and the movement might miss the target. The time it takes to adapt an action to unexpected environmental changes is clearly of great theoretical and practical interest, for example in driving an automobile.

Studies of the synchronization threshold, reviewed earlier, assessed a corresponding temporal constraint in the auditory domain, but they did so somewhat indirectly, using a periodic movement and a crude measure of synchronization failure. The present study investigated the temporal requirements of phase correction in a more direct fashion by using a perturbation technique comparable to the methods employed in the visuo-spatial perturbation studies just cited. The question of interest was: How much time must elapse between a timing perturbation and the next tap before that tap exhibits an adjustment in its timing, a *phase correction response* (PCR)?

The task involved synchronization with a two-interval (short-long) rhythm containing intermittent timing perturbations (Repp et al. 2008, 2010a). Such a rhythm can also be described as a cyclically repeated group of two tones (the *rhythmic group*), with the longer interval functioning as the between-group interval (IOI_b) and the shorter interval constituting the within-group interval (IOI_w). Participants tapped with every tone of the rhythm, using the two hands in alternation to avoid biomechanical rate limits of unimanual tapping (see Footnote 1). Perturbations were applied to IOI_b, and the PCR of the next tap, which followed IOI_w,

was assessed.[2] The duration of IOI_w was manipulated to range from 100 to 300 ms. If the synchronization threshold results reviewed earlier reflected the time it takes to carry out phase correction, the PCR should be minimal at IOI_w = 100 ms and increase gradually as IOI_w is increased. The alternative hypotheses considered by Repp (2006b) do not necessarily make that prediction: Limits on attentional entrainment and perceptual binding of events should not affect the PCR to the perturbed first tone in a rhythmic group, which follows IOI_b. However, binding of the taps in a rhythmic group into a tight action unit could well play a role in inhibiting the PCR, because it is the timing of the second tap in the group that must be adjusted. This hypothesis was also considered.

Experiment 1 tested the basic prediction that the PCR would emerge gradually as IOI_w increases. Two subsequent experiments employed variants of the task in which, respectively, the first tap or the second tone was omitted in each cycle. Experiment 2 thus tested whether the emergence of the PCR as a function of time would depend on the presence of a tap-tone asynchrony at the point of perturbation, and also to what extent the PCR might be limited by temporal binding of the two taps in a rhythmic group. Experiment 3 examined whether the PCR requires a synchronization target for the critical tap or whether it occurs automatically even in the absence of a target. In addition, each experiment yielded results concerning the accuracy of rhythm production or synchronization, which are of some theoretical interest and therefore will be discussed briefly.

Experiment 1

The experimental paradigm is illustrated schematically in Fig. 1a. The figure illustrates a positive phase shift in the pacing rhythm (i.e., lengthening of a single IOI_b caused by a delay of the tone terminating that interval and of all subsequent tones) and the PCR of the subsequent tap (in this case, also a delay). A negative phase shift would consist of a shortened IOI_b, followed by an advancement of the next tap. The idealized PCR in the illustration compensates completely for the phase shift, which implies a corresponding lengthening of the short (within-group) inter-tap interval but no change in the short tone–tap interval. If there were no PCR, the short inter-tap interval would not change, whereas the short tone–tap interval would. Typically, the PCR is between these two extremes, with phase correction being imperfect initially and completed in subsequent taps.

[2] To be precise, the next tap followed a short interval that was similar in duration to IOI_w and started either with the preceding tone (tone-tap interval) or the preceding tap (inter-tap interval).

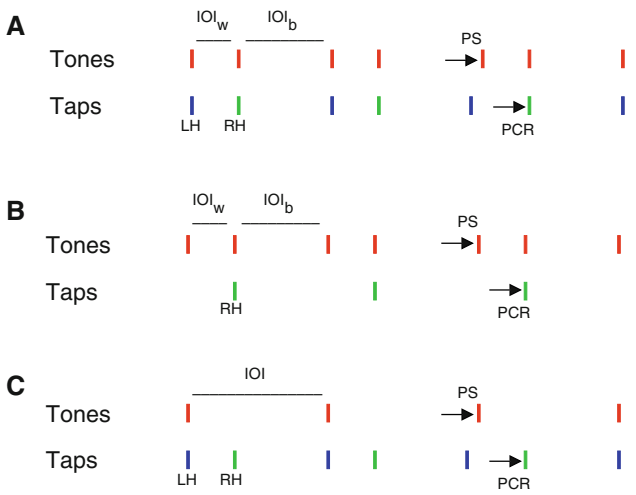

Fig. 1 Schematic illustration of the synchronization paradigms in (**a**) Experiment 1, (**b**) Experiment 2, and (**c**) Experiment 3. IOI_w within-group inter-onset interval, IOI_b between-group inter-onset interval, *LH* left hand, *RH* right hand, *PS* phase shift, *PCR* phase correction response. Some participants had the opposite hand assignment

It was assumed that the use of alternating hands does not affect the PCR. Although not well documented with data in the literature (but see Pressing 1998, and an unpublished study by Repp 2004a), this assumption follows naturally from the phase resetting hypothesis, according to which the PCR is a reaction to tones (which are not hand-specific) rather than to asynchronies (which are). If the PCRs were based on an asynchrony, there would be a theoretical possibility that it is based partially or wholly on the asynchrony in the same rhythmic position, which is associated with the same hand. In that case, the PCR to the immediately preceding asynchrony might be small or absent. On the basis of available data, this was considered unlikely.

A secondary question of interest was the accuracy with which the various rhythms, created by varying IOI_w as well as cycle duration, were produced during synchronization. It is well known that two-interval rhythms tend to be systematically distorted in production, typically in the direction of the simple 1:2 ratio which seems to function as an attractor (Povel 1981; Summers et al. 1986, 1989). Such distortions are observed even when highly trained musicians tap in synchrony with an exact auditory template (Repp et al. 2005, 2010a, b). However, there is no evidence so far that the next-simplest interval ratio, 1:3 serves as an attractor. Rather, production of 1:3 usually tends to shift in the direction of 1:2. The relatively small IOI_w/IOI_b ratios used in the present experiment, which included the 1:3 (.33) ratio, offered an opportunity to re-investigate this issue. If the 1:3 ratio served as a local attractor, musicians should produce it accurately, and a rhythm with a slightly larger ratio should be attracted toward 1:3 rather than (or as well as) to 1:2.

Methods

Participants

The 11 participants were all musically trained. They included 8 graduate students and one postgraduate of the Yale School of Music (5 men and 4 women, ages 22–26) who were paid for their efforts, an undergraduate research assistant (age 20), and the author (age 65). The musicians were regular participants in synchronization and perception experiments in the author's laboratory. Their primary instruments were piano (2), violin (3), viola, cello, oboe, and bassoon, which they had studied intensively for 13–21 years. The research assistant, too, had extensive training as a pianist, and the author is a lifelong amateur pianist.

Materials and equipment

Tone sequences were generated on-line by a program written in MAX 4.0.9, running on an Intel iMac computer. The tones (piano timbre) were produced by a Roland RD-250s digital piano according to instructions from the MAX program and were presented over Sennheiser HD280 pro headphones. All tones had the same pitch (C4, 262 Hz), the same nominal duration (40 ms), and the same comfortable intensity. In the absence of perturbations, cycle duration ($= IOI_w + IOI_b$) was fixed at either 800 or 1,200 ms and IOI_w was 100, 150, 200, 250, or 300 ms, which resulted in ten rhythms. The reason for varying cycle duration was to confirm that the critical variable for the PCR is the absolute duration of the tone–tap interval accompanying IOI_w, not the relative phase of the tone initiating it. Each rhythmic pacing sequence (trial) contained 10 phase shifts (i.e., changes of a single IOI_b, without any change in IOI_w) whose magnitudes ranged from −50 to 50 ms in steps of 10 ms (not including zero). They occurred in random order and were separated by 2–5 unperturbed cycles, this number also being a random variable; hence, the number of cycles varied from trial to trial.

Procedure

Participants sat facing the computer and tapped with alternating hands on the upper left and upper right segments of a Roland SPD-6 electronic percussion pad, held on the lap. Six participants tapped left–right with each group of two tones (as indicated in Fig. 1a), whereas five were given the opposite hand assignment (no effect of this variable was expected). They were instructed to start tapping with the third group of tones in each sequence and to keep tapping in synchrony with the tones until they stopped. It was pointed out that some small deviations from regularity might occur in the pacing rhythm. Each participant completed five blocks of ten trials each, with the ten randomly ordered trials representing the ten rhythms. The session took less than an hour.

Analysis

Asynchronies were computed by subtracting the onset time of each tone from that of the corresponding tap so that a negative asynchrony indicated that the tap preceded the tone. Then, for each individual phase shift, the asynchrony at the phase shift was subtracted from the following asynchrony, and these differences for the same phase shift magnitude in the same rhythm were averaged across the five trial blocks. The resulting numerical values, let us call them PCR*, consisted of two additive components: the PCR itself (i.e., the shift of the tap following the phase shift relative to when it would have occurred in the absence of a phase shift) and the expected difference between the asynchronies in the two rhythm positions (which would be zero only if the rhythm were not systematically distorted in production). By subsequently plotting PCR* as a function of phase shift magnitude and fitting a regression line, the two components could be separated: The slope of the regression line was an estimate of the mean PCR (expressed as a proportion of phase shift magnitude, because a phase shift of zero implies a zero PCR), whereas the intercept estimated the average amount (in ms) by which IOI_w was lengthened and IOI_b was shortened in production. All data were subjected to repeated-measures ANOVAs, with the Greenhouse-Geisser correction applied to *P* values whenever this was applicable.

Results

Figure 2 shows scatter plots and regression lines for PCR* data averaged across all participants. The strong linearity of the average functions was fully expected, as the PCR generally varies as a linear function of perturbation magnitude as long as the changes in IOI duration are relatively small (Repp 2002b); this has also been shown to be the case in synchronization with two-interval rhythms (Repp et al. 2010a). In addition, the figure shows that the slopes of the regression lines increased with the duration of IOI_w, that the slopes were similar for the two cycle durations, and that the intercepts were also similar, except at $IOI_w = 300$ ms.

Figure 3a summarizes the slope (= mean PCR) results. Here it can be seen that, as predicted, the mean PCR increased gradually during the range of IOI_w durations, in a similar way for both cycle durations. An ANOVA on individual participants' slope estimates with the within-participant variables of cycle duration and IOI_w duration, and the between-participant variable of hand assignment yielded a single significant effect, that of IOI_w, $F(4, 36) = 47.16$,

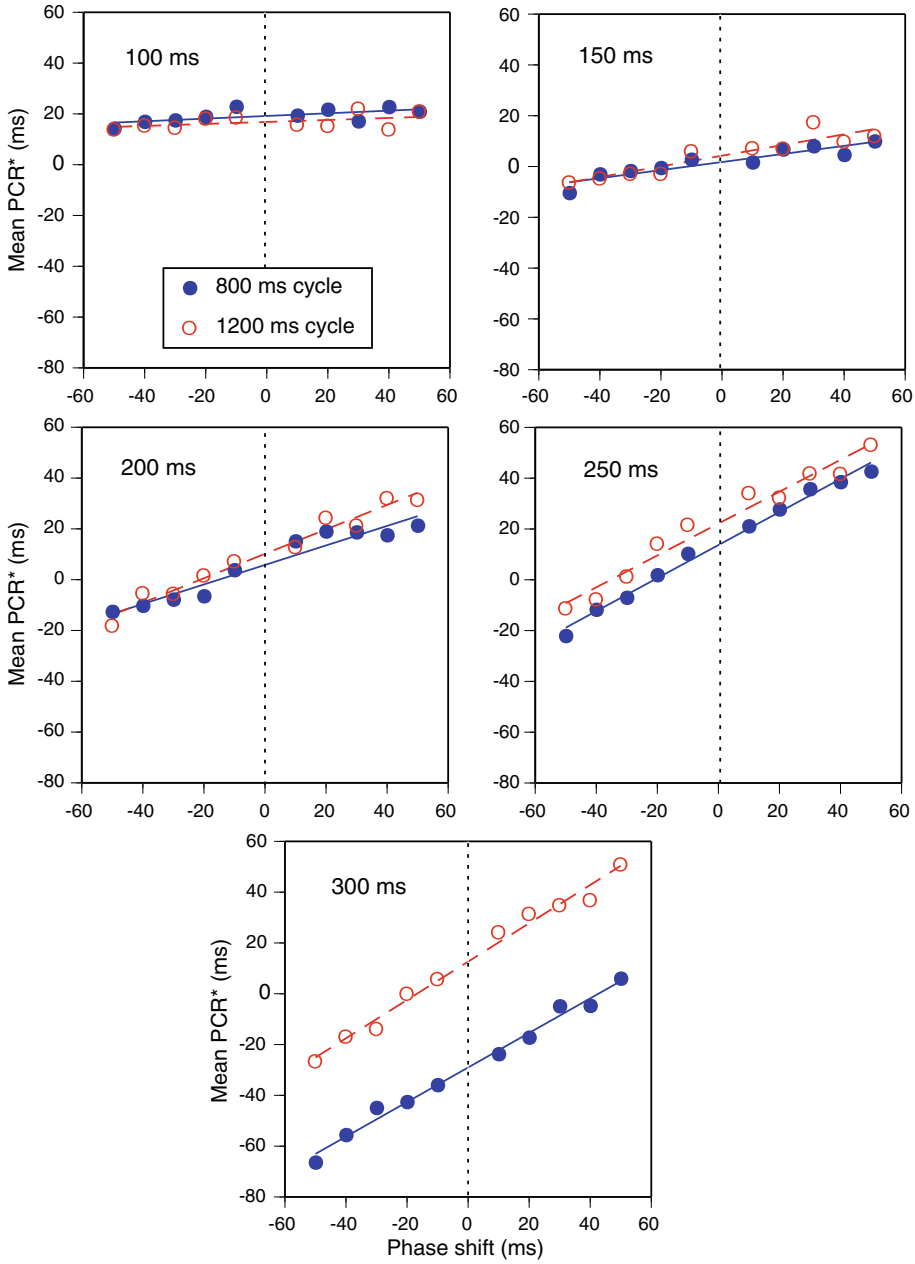

Fig. 2 Relation between mean PCR* and phase shift magnitude for the two cycle durations. *Each panel* is for a different duration of IOI_w

$P < .001$. Thus, neither cycle duration nor hand assignment made any difference to the PCR. At $IOI_w = 100$ ms, *t* tests revealed a significant difference from zero for the 800-ms cycle duration, $t(10) = 2.85$, $P = .017$, but not for the 1,200-ms cycle duration, $t(10) = 1.58$, $P = .144$.

Although IOI_w was the crucial independent variable, the interval most relevant to the PCR, according to the phase resetting hypothesis, is the one between the tone initiating IOI_w and the tap intended to be synchronized with the tone that terminates IOI_w. That tone–tap interval is not only variable due to biological noise but also is likely to differ in its mean duration from IOI_w. To calculate its mean duration, the mean asynchrony associated with the tone that terminated IOI_w was first determined for each of the ten rhythms (taps exhibiting a PCR were included in this average, as shortened and lengthened asynchronies due to phase correction were expected to cancel out). Mean asynchronies were all negative; thus, taps preceded tones, as is commonly found in synchronization tasks. This anticipation tendency was marginally greater at the shorter cycle duration, $F(1, 10) = 4.98$, $P = .05$, and increased with IOI_w, $F(4, 40) = 8.66$, $P = .003$, more so at the shorter cycle duration, $F(4, 40) = 4.43$, $P = .029$. The mean (negative) asynchrony was added to IOI_w to obtain the mean short tone–tap interval for each rhythm. Figure 3b re-plots the mean PCR as a function of that interval. The functions are similar to those in Fig. 3a but shifted to the left, due to the fact that the short tone–tap intervals were shorter than IOI_w. It can

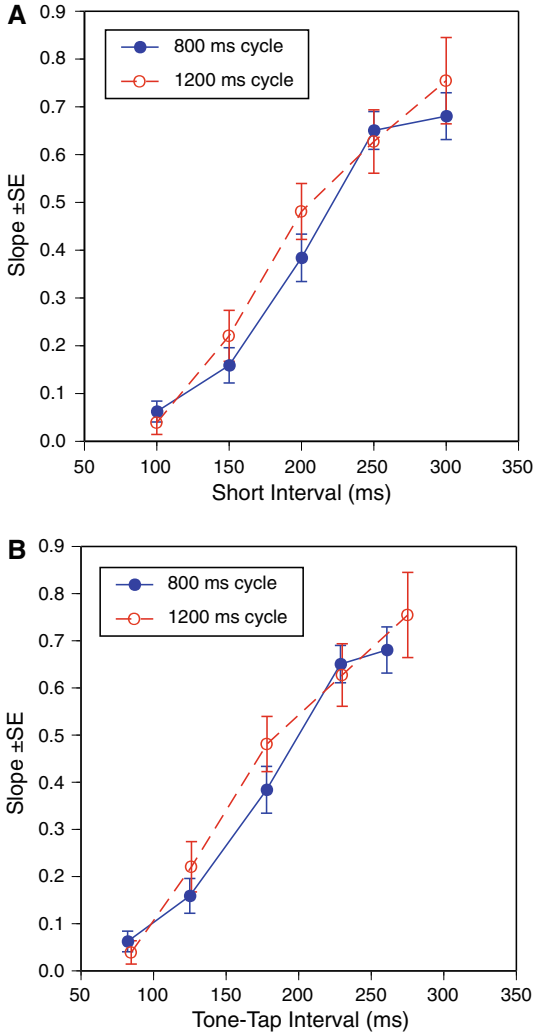

Fig. 3 Slope of the regression line (i.e., the mean PCR) as a function of (**a**) short interval (IOI_w) duration and (**b**) tone–tap interval duration, for the two cycle durations

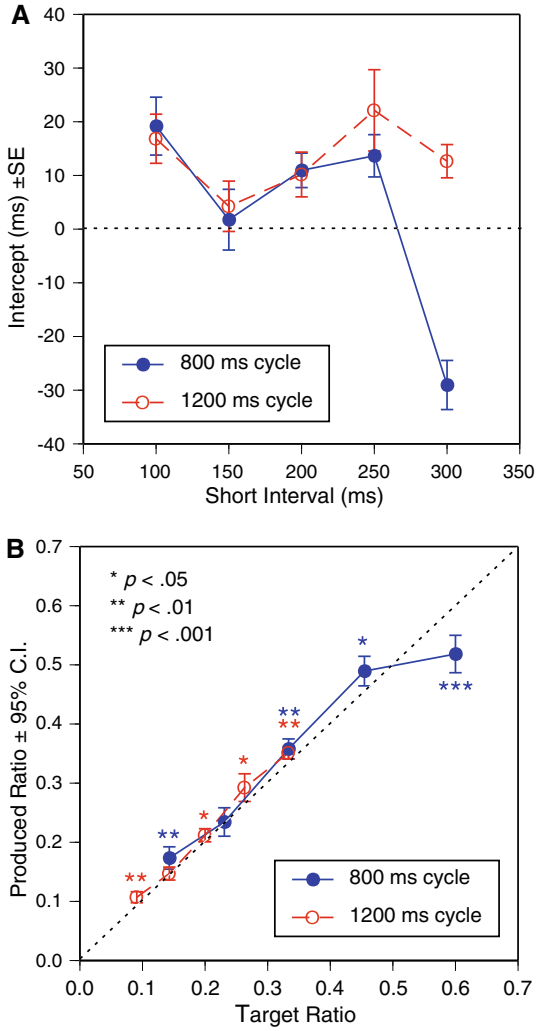

Fig. 4 **a** Intercept of the regression line as a function of IOI_w duration, for the two cycle durations. **b** Produced interval ratio as a function of target interval ratio, with 95% confidence intervals and significance levels of deviations from accurate production (*diagonal line*)

be concluded that the PCR began to emerge even before 100 ms, on average, had elapsed after the preceding tone.

There is one further aspect of the data not considered so far. When a phase shift occurred, the tone preceding the tap exhibiting the PCR occurred up to 50 ms earlier or later than expected. It seems that this should have introduced an additional asymmetry: A negative phase shift (where the tone occurs earlier than expected) leaves more time to adjust than does a positive phase shift (where the tone occurs later than expected). Of course, having to advance the next tap in one case and delay it in the other would to some extent nullify this asymmetry. Nevertheless, one might expect the slope of the PCR* functions in Fig. 2 to be shallower on the positive than on the negative side, especially for intermediate values of IOI_w. A trend in that direction can indeed be seen with the naked eye. To test its reliability, slopes of the PCR* function were calculated separately for negative and positive phase shifts at each of the three intermediate IOI_w durations and for each cycle duration, and submitted to a three-way ANOVA. In addition to the predictable main effect of IOI_w duration, there was also a significant main effect of phase shift direction, $F(1, 10) = 11.25$, $P = .007$, confirming that the slopes were steeper for negative than for positive phase shifts. This indicates a fairly robust effect, for the slopes for individual participants (each based on only five data points, each of which was the average of five raw data points) were quite variable.

To address the secondary question of interest, concerning the accuracy of rhythm production, Fig. 4a summarizes the intercept results from Fig. 2. An ANOVA on these data revealed, besides significant main effects of cycle duration and IOI_w duration, a significant two-way interaction, $F(4, 36) = 11.70$, $P = .001$, due to the large effect of cycle

duration at IOI_w = 300 ms. With that IOI_w duration omitted, only the main effect of IOI_w was significant, $F(3, 27) = 8.71$, $P = .002$, due to a smaller intercept at IOI_w = 150 ms.

Figure 4b shows the rhythm production results in terms of inter-tap interval ratios derived from the intercepts: produced ratio = $(IOI_w + I)/(IOI_b - I)$, where I = intercept. The mean produced ratio is shown as a function of the target ratio (IOI_w/IOI_b). Although most rhythms were produced rather accurately, the majority nevertheless showed significant deviations from the target ratio in the upward direction, namely toward 1:2 (.5). This was also true for the two rhythms that had a target ratio of 1:3 (.33). The largest deviation by far was shown by the only rhythm whose target ratio exceeded .5 (viz., 300/500 ms = .6). That rhythm was produced with a much smaller ratio, .518 on average, which is very close to 1:2.

Discussion

The PCR results of Experiment 1 seem consistent with the earlier findings on the synchronization threshold (Repp 2003b, 2007) in that they suggest that immediate phase correction vanishes as IOI duration approaches 100 ms. In synchronization with an isochronous sequence, where many short IOIs follow upon another, this is likely to result in phase wrapping; whereas in synchronization with a two-interval rhythm, it results only in a failure to react immediately to a phase shift, with the phase correction being postponed to the next tap (which follows a long interval). Thus, there is no disruption of synchronization.

It is not clear whether the PCR reached an asymptote at IOI_w = 300 ms, but it was quite large and actually larger than that obtained in a recent experiment in which a partially identical group of participants tapped unimanually with a two-interval rhythm having the same IOI_w duration (Repp et al. 2010a: Fig. 5). This comparison incidentally also confirms the assumption that the PCR would readily occur across hands. If anything, dividing taps between hands may have resulted in increased flexibility of timing, thereby increasing the PCR. The absence of an effect of cycle duration furthermore confirms the prediction that the PCR would be dependent on the absolute time elapsing since the preceding tone, not on the relative phase of that tone within the rhythm cycle.

The results concerning rhythm production accuracy confirm earlier findings (Povel 1981; Summers et al. 1986, 1989), showing attraction toward the 1:2 ratio (or some other ratio in its close vicinity; Repp et al. 2010b), especially if the target ratio is close to 1:2. There is still no evidence that the 1:3 ratio functions as a local attractor, despite its importance in music (e.g., dotted eighth-note plus sixteenth-note). One unexpected and potentially important finding is that for IOI_w durations shorter than 300 ms, the accuracy of rhythm production did not depend on the IOI_w/IOI_b ratio. This may be related to Fraisse's (1956) distinction between short and long durations (*temps court* and *temps long*), with the former being perceived as linking events rather than as intervals. Also relevant is the fact that Weber's law ceases to hold (even approximately) for intervals much shorter than 300 ms (Clarke 1989; Hibi 1983; Peters 1989). Short intervals thus may tie events into rhythmic groups without entering into relationships with longer intervals.

Experiment 2

In Experiment 1, it was assumed that the factor limiting the PCR is the time elapsing between the phase-shifted tone and the next tap. However, there may be another factor operating: The two taps in a rhythmic group follow closely upon each other and thus may be tightly bound together as an action unit. Such a unit may become increasingly inflexible as the inter-tap interval decreases along with IOI_w; essentially, the two movements may be planned and executed as a single action, so that the timing of the second tap in the group cannot be adjusted easily. Thus, the results of Experiment 1 may reflect not only a temporal limit of phase correction but also temporal constraints due to bimanual motor planning and execution.

Experiment 2 addressed this issue by requiring participants to make only a single tap in each cycle, in synchrony with the second tone in each rhythmic group, as illustrated schematically in Fig. 1b. To the extent that the PCR in Experiment 1 was limited by inflexibility of bimanual coordination, it should increase in Experiment 2. At the same time, a temporal constraint on phase correction should still be evident.

Omitting the first tap in each rhythmic group also eliminates the asynchrony between that tap and the phase-shifted tone. According to traditional conceptions of phase correction, it is this asynchrony that triggers the PCR, and so the PCR should be reduced or even absent when there is no asynchrony signaling the phase shift. However, if the PCR reflects phase resetting based on the preceding tone, absence of an asynchrony should not matter. This has been shown to be the case with isochronous pacing sequences (Repp 2001); in fact, the PCR increased when the preceding tap was omitted, which was attributed to a reduction in the maintenance tendency. Experiment 2 investigated whether this also applies to non-isochronous sequences. Omission of the first tap in each rhythmic group can be regarded as reducing the tendency to maintain a constant short interval between the two taps in a rhythmic group and thereby releasing the PCR from inhibition.

An aspect of secondary interest in Experiment 2 was the mean asynchrony of the taps as a function of IOI_w. A

two-interval rhythm can be regarded as two interleaved isochronous sequences with a certain phase relationship or temporal offset (i.e., IOI_w). Synchronization with one such sequence (the target) was studied by Repp (2003b), who found that the taps were attracted to the tones of the other sequence (the distracter), without participants being aware of this. Especially when the distracter tones preceded the target tones, the negative mean asynchrony increased, and this increase was largest at a temporal separation of about 80 ms and did not seem to depend on cycle duration. As the present IOI_w durations were all longer than 80 ms, the expectation was that the mean negative asynchrony would decrease as IOI_w increased, reflecting decreasing attraction to the tones preceding the target tones.

Methods

Participants

Two of the participants from Experiment 1 (the bassoonist and the undergraduate research assistant) were no longer available, but the other 9 returned for Experiment 2.

Materials and equipment

These were the same as in Experiment 1, but as cycle duration had had no effect on the PCR in Experiment 1, only the shorter cycle duration (800 ms) was used. Thus, there were only five trials in each block.

Procedure

Each participant completed six blocks of trials in a 1-h session that also included Experiment 3, with order of experiments approximately counterbalanced across participants. Participants tapped unimanually with their preferred hand (one was left-handed) in synchrony with the second tone in each rhythmic group.

Analysis

The asynchrony between taps and target tones was calculated as previously. However, as there was no asynchrony with the phase-shifted tone immediately preceding the PCR, the PCR was calculated as the current asynchrony minus the preceding asynchrony in the same rhythm position, plus the phase shift magnitude.[3] The PCR values thus obtained were averaged across trial blocks and then regressed onto phase shift magnitude, separately for each IOI_w duration. These regression lines, unlike those in Experiment 1, passed through the origin, or nearly so.[4] The slope of the regression line again served as an estimate of the mean PCR. The mean asynchrony in each IOI_w condition was computed by averaging across all asynchronies within and between trials.

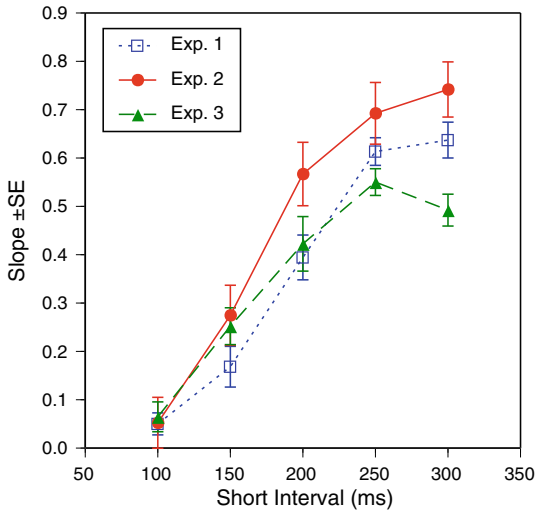

Fig. 5 Slope of the *regression line* (i.e., the mean PCR) as a function of IOI_w duration in Experiments 1 ($N = 9$), 2, and 3

Results

The PCR results are shown as a function of IOI_w in Fig. 5, together with the results for the same nine participants in the 800-ms cycle duration condition of Experiment 1 (also included are the results of Experiment 3, to be discussed later). It is evident that the PCR increased as IOI_w increased, as in Experiment 1, but that the PCRs were somewhat larger. A two-way ANOVA confirmed this difference in magnitude, $F(1, 8) = 7.63$, $P = .025$. The interaction with IOI_w duration was not significant. Nevertheless, the mean PCRs at $IOI_w = 100$ ms were virtually identical in the two experiments.

The slopes of the PCR functions were again computed separately for negative and positive phase shifts, for the three intermediate values of IOI_w. Because the expected PCR is zero when the phase shift is zero, all regression lines were forced through the origin, which effectively added a data point and helped stabilize the slopes. A two-way ANOVA showed that the mean slope for negative

[3] Adding the phase shift magnitude ensured that the PCR was zero when there was indeed no PCR. Because all tones following the phase-shifted tone are phase shifted as well (see Fig. 1), the expected asynchrony of the critical tap in absence of a PCR is M–PS, where M is the expected asynchrony in that rhythm position and PS is the phase shift.

[4] Note that it does not matter whether or not they passed exactly through the origin. Because negative and positive phase shifts were symmetric around zero, forcing the regression line through the origin did not change its slope.

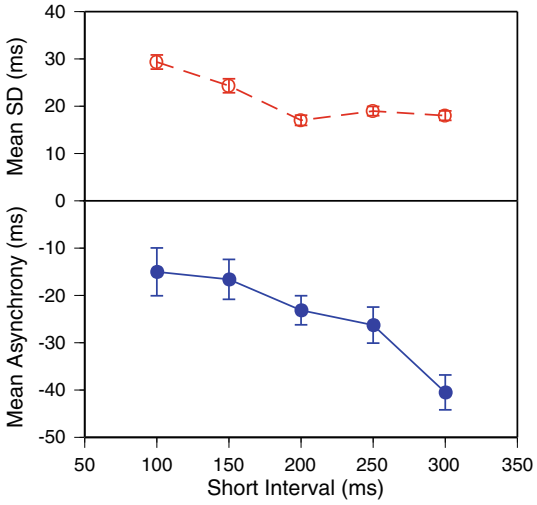

Fig. 6 Mean asynchrony (*below*) and mean within-trial standard deviation of asynchronies (*above*) as a function of IOI_w duration in Experiment 2. The *error bars* represent standard errors

phase shifts was again larger than that for positive phase shifts, $F(1, 8) = 5.56$, $P = .046$. Thus, the temporal constraint on the PCR was more severe with positive than with negative phase shifts. The interaction with IOI_w was not significant.

The mean asynchrony is shown as a function of IOI_w in the lower half of Fig. 6. It was negative at all values of IOI_w and decreased (i.e., became more negative) as IOI_w increased, $F(4, 32) = 21.70$, $P < .001$, contrary to predictions based on earlier target-distracter experiments. Although the decrease was most pronounced at the longest IOI_w, the quadratic trend fell just short of significance, $F(1, 8) = 4.86$, $P = .058$. At the same time, the mean within-trial variability of the asynchronies (shown in the upper half of Fig. 6) decreased, $F(4, 32) = 38.60$, $P < .001$. This decrease deviated significantly from linearity, having significant second- and fourth-order components, because it extended only from 100 to 200 ms, with variability being constant thereafter.

Discussion

The PCR results confirm that an asynchrony with the preceding phase-shifted tone is not necessary to elicit a PCR (Repp 2001). It could be countered that in the absence of a tap-tone asynchrony, the PCR is driven by the asynchrony between an internally generated temporal expectation and the onset of the phase-shifted tone (Jones and Boltz 1989; Jones and Yee 1997; Yee et al. 1994). To explain the linear relation between the PCR and phase shift magnitude, however, this mechanism would have to be sensitive to asynchronies and timing deviations that are not consciously detectable, which is problematic because it has been proposed to explain conscious temporal judgments. It is more straightforward to attribute the PCR to tone-based phase resetting, in which case no asynchrony or timing deviation needs to be perceived, consciously or subconsciously. Rather, only an interval needs to be timed from the preceding tone. Such phase resetting plus inhibition due to a rhythm maintenance tendency is a discrete equivalent of the dynamic-systems phenomenon of coupling or entrainment, which likewise is not mediated by conscious perception, being derived from physics.

The finding of somewhat larger PCRs in Experiment 2 than in Experiment 1 suggests that temporal binding of the two taps in a rhythmic group may have hampered the PCR somewhat in Experiment 1. Removing the short interval from the tapping rhythm by omitting one tap in each cycle resulted in the creation of a long inter-tap interval (800 ms), which afforded greater temporal flexibility. However, the lower limit of the PCR (near $IOI_w = 100$ ms) remained unaffected.

The decrease (i.e., increasing negativity) in mean asynchronies as IOI_w increased does not agree with the previous findings of Repp (2003a, b) on phase attraction in synchronization with interleaved isochronous sequences. According to those findings, the negative mean asynchrony should have been most pronounced at the shortest IOI_w, due to attraction of the taps to the preceding tones, and should have become smaller at longer values of IOI_w. However, the mean asynchronies were very similar to those in the corresponding rhythm position in Experiment 1, which suggests that they were determined by participants' conception of the pacing sequence as constituting a unitary rhythm (rather than being composed of isochronous target and distracter sequences). This conception was surely aided by the fact that the sequences were monotone.

The increase in variability of asynchronies at short values of IOI_w is more consistent with the phase attraction results, which had shown a peak in variability when targets and distracters were separated by 100 ms. Evidently, when tones follow each other at intervals shorter than 200 ms, it becomes more difficult to target the second tone reliably (see also Repp 2003b, a.) This may again be related to the event-binding function of such short intervals (Fraisse 1956).

Experiment 3

Experiment 3 investigated whether the tap following a phase shift must have a synchronization target in order for it to exhibit a PCR. Here participants tapped a two-interval rhythm (cued by a brief initial induction sequence) in synchrony with a simple metronome, such that the first tap in each rhythmic group coincided with a tone, as illustrated in

Fig. 1c. In other words, the second tone in each rhythmic group of the pacing sequence was omitted. Because the corresponding tap was now without a synchronization target, there was no need for a PCR to occur on that tap. Participants could simply keep the interval between the taps in a rhythmic group constant and implement phase correction at the beginning of the next group. However, if the PCR is largely automatic, as earlier research has suggested (Repp 2002a, b), it should occur even without a synchronization target. If so, it should also be subject to the temporal constraints revealed in Experiments 1 and 2.

As in Experiment 1, a secondary aspect of interest was the accuracy of rhythm production. In this experiment, participants had to remember the rhythm that was to be produced on each trial, and accuracy under those conditions could be compared to accuracy in Experiment 1, where participants had tapped in synchrony with an exact auditory template of the rhythm. Previous comparisons of synchronization and continuation of non-isochronous rhythms within the same experiment (Repp et al. 2005, 2010a) have revealed little difference in accuracy, but these experiments had task phases of similar duration whereas the present experiment had only a very brief induction (synchronization) phase.

Methods

Participants

The participants were the same as in Experiment 2.

Materials and equipment

These were the same as in Experiment 2, except that after the fifth cycle of the pacing sequence, the second tone in each rhythmic group was omitted. This resulted in an intermittently perturbed isochronous pacing sequence with baseline IOIs of 800 ms. Phase shifts were introduced in the same way as previously.

Procedure

Each participant completed six blocks of five trials each in a 1-h session that also included Experiment 2, which came first for some participants. Participants tapped with alternating hands, as in Experiment 1. As there had not been any effect of hand assignment in Experiment 1, participants were asked to tap in the way they preferred, which was left–right (as indicated in Fig. 1c) for all but one. They started tapping with the third group of tones and thus synchronized with three two-tone groups before the pacing sequence turned into a simple metronome. They were instructed to maintain the rhythm that was established initially and to synchronize the first tap of each two-tap group with the metronome.

Analysis

The data were analyzed as in Experiment 1, except for exclusion of the hand assignment variable.

Results

The mean PCR is shown as a function of (sequence-initial) IOI_w duration in Fig. 5, together with the results of Experiments 1 and 2 for the same participants. It is evident that a PCR did occur, and its size was comparable to that in Experiment 1; only at the longest IOI_w was the PCR smaller in the present experiment. A two-way ANOVA comparing the data from Experiments 1 and 3 showed the main effect of experiment not to be significant; however, the Experiment × IOI_w interaction was reliable, $F(4, 32) = 4.61$, $P = .009$. If $IOI_w = 300$ ms was omitted, the interaction was no longer significant.

Mean PCRs (slopes) were again calculated separately for negative and positive phase shifts, for the three intermediate IOI_w durations. Once again, the slopes tended to be steeper for negative than for positive phase shifts, but the difference fell short of significance here, $F(1, 8) = 4.22$, $P = .074$.

The average accuracy of rhythm production is shown in Fig. 7, which also includes the data from Experiment 1 for the same participants. Figure 7a shows the intercept results, whose pattern was quite similar to that observed in Experiment 1. However, all intercepts were higher here (more positive), which implies that the short inter-tap interval was generally longer than in Experiment 1, and the long inter-tap interval was shorter. A two-way ANOVA showed this difference to be significant, $F(1, 8) = 16.96$, $P = .003$, and it did not interact with IOI_w duration. Consequently, as can be seen in Fig. 7b, the smaller ratios deviated more from their target ratios than they did in Experiment 1, whereas the largest ratio deviated less. All individual deviations were significant by *t* tests. The pattern of deviations confirms the general attraction toward the 1:2 ratio, with no evidence of an attractor at 1:3.

Discussion

The results of Experiment 3 are sufficiently similar to those of Experiment 1 to allow the conclusion that the PCR happened automatically, even in the absence of a synchronization target for the critical tap and even though participants were instructed to maintain the initial rhythm. Only at $IOI_w = 300$ ms was the PCR reduced somewhat, perhaps due to some participants' deliberate efforts not to change

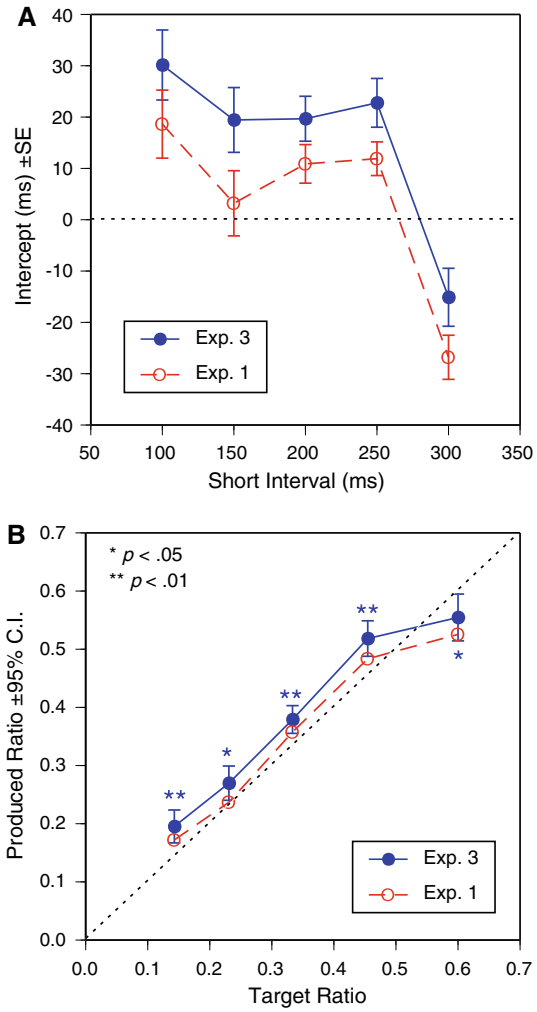

Fig. 7 **a** Intercept of the regression line as a function of IOI_w duration in Experiment 3, with corresponding data ($N = 9$) from Experiment 1. **b** Produced interval ratio as a function of target interval ratio, with 95% confidence intervals and significance levels of deviations from accurate production (*diagonal line*) in Experiment 3, with corresponding data ($N = 9$) from Experiment 1

their tapping rhythm. One participant commented after the experiment that he had wondered whether he should adjust to the perturbations or resist such adjustments and that he had decided to resist (the instructions had not been explicit on that point). His results showed hardly any PCR at the three shorter IOI_w durations, but substantial PCRs at the two long durations. Thus, he was not able to suppress the PCR, except possibly at intermediate IOI_w durations. It is known that the PCR can be reduced voluntarily in synchronization with isochronous sequences (Repp 2002a, b), but to what extent this is possible in the present task remains to be investigated.

The rhythm production results, in comparison with those of Experiment 1, confirm the previously observed similarity of timing patterns in synchronization and continuation (Repp et al. 2005, 2010a), even though the present induction sequence was very brief. The observed systematic lengthening of the short interval, relative to Experiment 1, could be due to increased force of the first tap in each rhythmic group, because only that tap had a synchronization target and thus was likely to be perceived as the metrically stronger element in the group. It is known that intervals following an accented tap tend to be lengthened (Billon and Semjen 1995; Billon et al. 1996; Semjen and Garcia-Colera 1986). However, whether the first tap was actually accented was not investigated here.

Summary and conclusions

The present study investigated temporal constraints on phase correction in the context of non-isochronous (two-interval) rhythms. Experiment 1 showed that the PCR to a phase perturbation requires at least about 100 ms to emerge and then increases gradually up to 250 or 300 ms. These results complement earlier findings concerning the synchronization threshold (Repp 2002a, b, 2005a, 2007), which had indicated that synchronization with isochronous sequences becomes difficult when IOIs are smaller than about 125 ms. It should be emphasized that these limits pertain to highly trained musicians; people with less or no musical training may need more time (Repp 2007), although within the present paradigm this remains to be confirmed empirically.

Experiments 2 and 3 supplemented Experiment 1 by showing that the PCR is not contingent on a preceding asynchrony, is somewhat constrained by bimanual coordination, and occurs in the absence of a synchronization target for the critical tap, while the temporal constraints remained similar to those in Experiment 1. All results are consistent with the hypothesis that the PCR constitutes phase resetting with reference to the preceding tone (Hary and Moore 1985, 1987; Repp 2001, 2005b, 2008), with added inhibition due to a tendency to maintain the established rhythm.

Recent studies have examined the temporal evolution of phase correction when a continuous movement is synchronized with a perturbed metronome. Phase correction emerged gradually within the first cycle following a perturbation, though more slowly than in discrete movements (Repp 2010; Repp and Steinman 2010; Torre and Balasubramaniam 2009). This can be attributed to a stronger maintenance tendency (i.e., inertia) when the movement is continuous.

The temporal limit demonstrated here can be interpreted as a kind of motor reaction time, namely the time needed to change the temporal goal of an incipient action. The PCR is an auditory-temporal analogue of the rapid visual-spatial correction that occurs in goal-directed movements when the

target or background is suddenly shifted (Brenner and Smeets 1997; Gomi 2008; Hansen and Elliott 2009; Paulignan et al. 1991) and thus is of considerable theoretical and practical interest.

The present experiments also furnished new data pertaining to the accuracy of two-interval rhythm production. The results are consistent with earlier findings that these rhythms tend to be distorted in the direction of 1:2, particularly if the target ratio is in the vicinity of that simple ratio. Such distortions occur even when highly trained musicians tap in synchrony with auditory templates. However, production of rhythms containing short intervals (<300 ms) was rather accurate on average and seemed to depend on the absolute duration of the short interval rather than on the short/long interval ratio. This is a new finding that bears on the different functions of short and long intervals in rhythm perception and production (Fraisse 1956).

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